

PB88-250550

Evaluation of Low-Emission Coal Burner
Technology on Industrial Boilers
Volume 3. Guideline Manual

Energy and Environmental Research Corp.
Irvine, CA

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Aug 88



U.S. Department of Commerce
National Technical Information Service

NTIS

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA/600/7-88/019c	2.	3. REPORT'S ACCESSION NO. 88-250550/AS
4. TITLE AND SUBTITLE Evaluation of Low-Emission Coal Burner Technology on Industrial Boilers; Volume III. Guideline Manual	5. REPORT DATE August 1988	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) B.A. Folsom, A.R. Abele, J.L. Reese, and T.M. Sommer	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Energy and Environmental Research Corporation 18 Mason Irvine, California 92714	10. PROGRAM ELEMENT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	11. CONTRACT/GRANT NO. 68-02-3127	
	13. TYPE OF REPORT AND PERIOD COVERED Final; 10/78 - 9/86	
	14. SPONSORING AGENCY CODE EPA/600/13	
15. SUPPLEMENTARY NOTES AEERL project officer is P. Jeff Chappell, Mail Drop 63, 919/541-3738. Vol. I is the technical report. Vol. II contains appendices.		
16. ABSTRACT The report gives results of a field evaluation of the Distributed Mixing Burner (DMB) on a 98 kg/hr (215,000 lb/hr) steaming capacity, four-burner, front-wall-fired boiler. Prior to the DMB retrofit, field tests established baseline operating conditions with the pre-NSPS (New Source Performance Standards) burners originally installed in the boiler. Following DMB installation, the boiler was operated and tested with the new burners for 17 months. Under routine operation, the DMBs reduced NOx emissions by about 50%--from the baseline condition of about 0.96 to about 0.46 lb/million Btu (418 to 200 ng/J). Under carefully controlled, optimized conditions, NOx emissions were further reduced about another 20%--to about 0.3 lb/million Btu (131 ng/J). The DMB is a low-NOx pulverized-coal burner for wall-fired boiler applications. It operates under reducing conditions in the primary flame zone to minimize NOx emissions while an overall oxidizing environment is maintained in the furnace to minimize slagging and corrosion. This operation is accomplished by using air ports around the burner throat to provide staged combustion conditions at each individual burner.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Burners Pulverized Fuels Combustion Nitrogen Oxides	Pollution Control Stationary Sources Distributed Mixing Burners (DMBs) Wall-Fired Boilers Staged Combustion	13B 13A 21D 21B 07B
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified 20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 94 22. PRICE \$14.95

EVALUATION OF LOW-EMISSION COAL BURNER TECHNOLOGY
ON INDUSTRIAL BOILERS

Volume III - Guideline Manual

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REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
SPRINGFIELD, VA. 22161

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ACKNOWLEDGMENT

This report was prepared for the Air and Energy Engineering Research Laboratory (AEERL) of the U.S. Environmental Protection Agency in Research Triangle Park, North Carolina. The authors wish to express appreciation to G. B. Martin and J. Chappell, the EPA Project Officers. The authors also wish to thank the technical staff of Energy and Environmental Research Corporation, Foster Wheeler Development Corporation and Foster Wheeler Energy Corporation, who conducted the experimental efforts. A field evaluation program requires the co-operation of a host utility. The authors wish to acknowledge the considerable support provided by D. Bringman, G. Rothering and the staff of Western Illinois Power Cooperative who provided access to Pearl Station Unit 1 for this program.

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The U.S. EPA has developed a low NO_x pulverized coal burner that accomplishes staged combustion by means of air ports located around a circular burner. This distributed mixing burner (DMB) allows a fuel rich combustion zone, with a stoichiometry in the optimum range for NO_x emission control, while maintaining an overall oxidizing atmosphere in the furnace minimizing the potential for water wall corrosion, slagging and carbon burnout problems. Several DMB configurations have been tested in research furnaces and a field evaluation has been conducted on a 20 MW utility boiler.

The DMB is not a specific burner design but rather is an approach to the design of low NO_x burners. DMBs have been designed and tested using components produced by four commercial burner manufacturers. This manual presents recommendations for the design of DMBs and their application to pulverized coal wall fired furnaces. It is intended for use by burner/boiler manufacturers, architect/engineers and owners/operators of combustion equipment to guide the use of the DMB to control NO_x emissions from industrial and utility combustion systems.

The remainder of this section presents the DMB concept and summarizes its development history focusing on the field evaluation. The details of the DMB development are presented in Volume I. Section 2 of this Guideline Manual presents recommendations for integrating the DMB concept with commercial burner components. Application considerations are discussed in Section 3.0. Finally, Section 4.0 discusses the performance of the DMB including flame characteristics, emissions and impacts on boiler operation.

1.1

DMB Concept

The DMB concept involves staging the combustion process to minimize NO_x emissions while maintaining an overall oxidizing atmosphere in the furnace to minimize slagging and corrosion. NO_x production from fuel nitrogen compounds is minimized by driving a majority of the compounds into the gas phase under fuel-rich conditions and providing a stoichiometry/temperature history which

maximizes the decay of the evolved nitrogen compounds to N_2 . Thermal NO_x production is minimized by heat loss from the fuel-rich zone which reduces peak temperatures.

A schematic representation illustrating how the DMB design stages the fuel/air mixing sequentially is shown in Figure 1-1. The combustion process occurs in three zones. In the first zone pulverized coal transported by the primary air combines with the inner secondary air to form a very fuel-rich (30 to 50 percent theoretical air) recirculation zone which provides flame stability. The coal devolatilizes and fuel nitrogen compounds are released to the gas phase. Outer secondary air is added in the second "burner zone" where the stoichiometry increase up to about 70 percent theoretical air. This is the optimum range for reduction of bound nitrogen compounds to N_2 . Air to complete the combustion processes is supplied through tertiary ports located outside the burner throat. This allows substantial residence time in the burner zone for decay of bound nitrogen compounds to N_2 and radiative heat transfer to reduce peak temperatures. The tertiary ports surround the burner throat providing an overall oxidizing atmosphere and minimize interactions between adjacent burners.

Figure 1-2 shows the installation of a typical DMB in a wall-fired boiler. The DMB design components illustrated are:

- Four independently controlled airstream systems divide the total combustion air into:
 1. A central airstream used for ignition during startup and cooling during normal operation (Stream A).
 2. The primary airstream carrying the coal (Stream B).
 3. Two concentric secondary airstreams to provide inner and outer secondary airflow (Stream C).
 4. Four outboard tertiary air ports (Stream E).

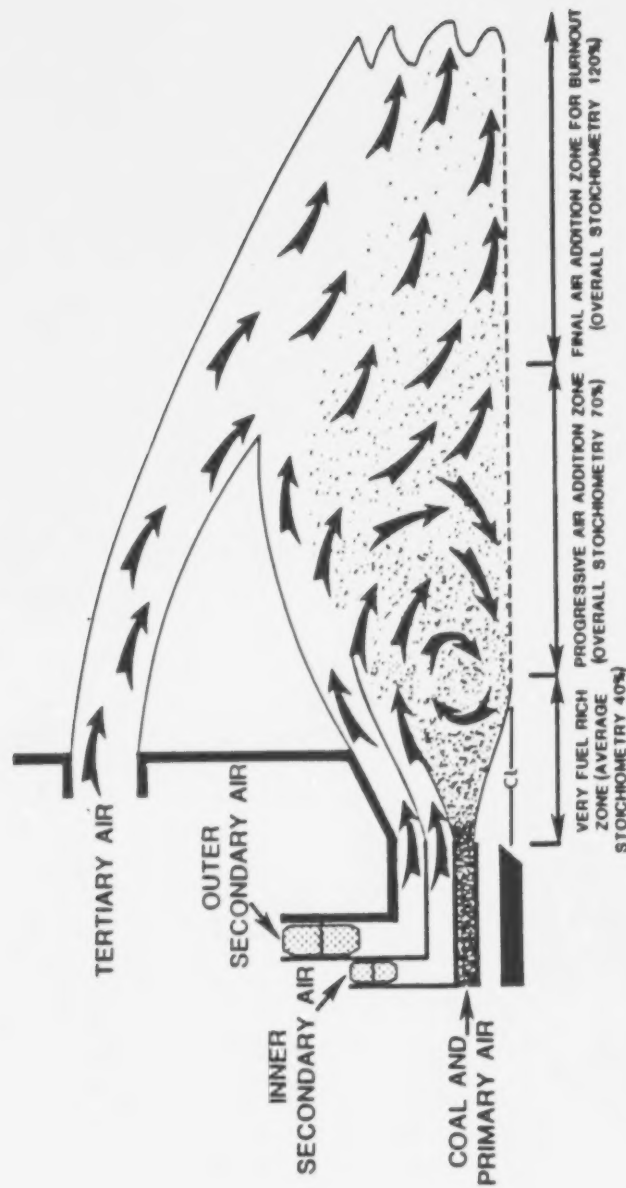
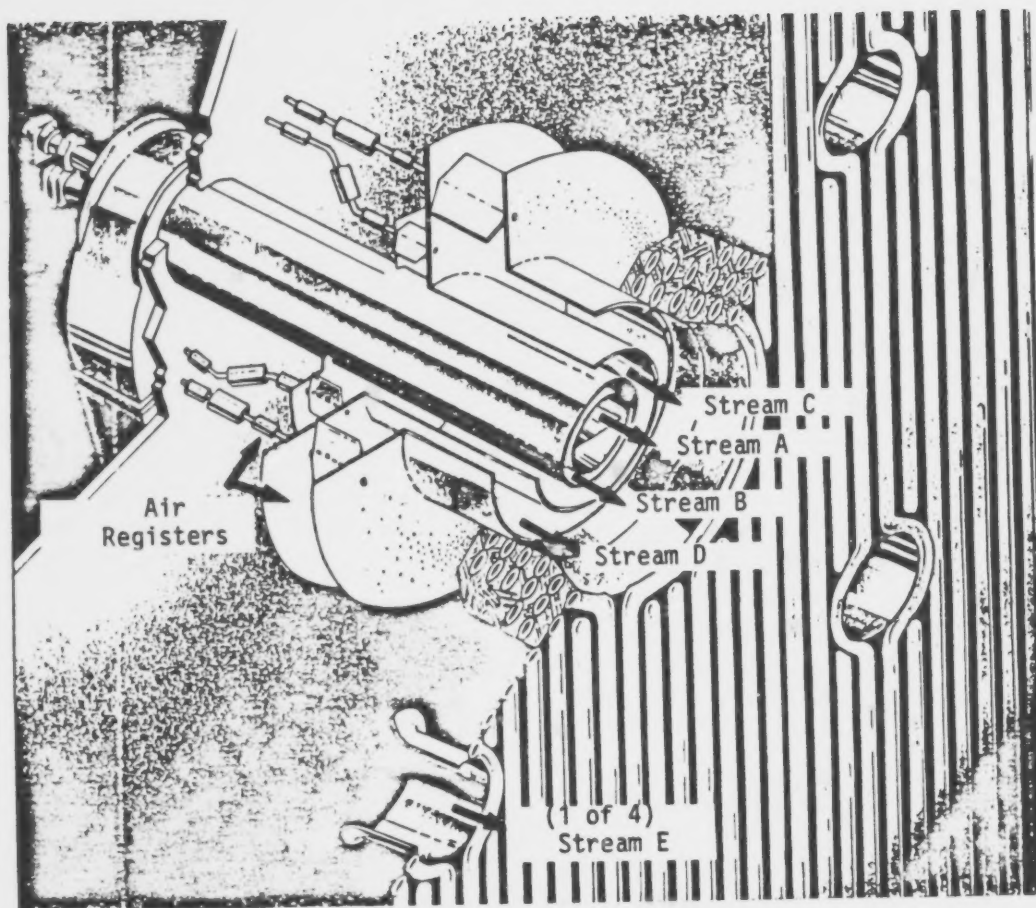


Figure 1-1. Distributed mixing burner concept.



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Figure 1-2. Distributed mixing burner.

- An annular fuel injector which produces a uniform annular coal distribution.
- Two adjustable air registers connected to the secondary air passages to control both the air flowrates and degree of swirl.
- A retractable oil atomizer on the burner axis.
- Ignition and main flame scanner systems for safety. Alternate DMB designs could include central coal nozzles, single secondary air passages or other design changes. The key element is the use of outboard tertiary air ports to achieve staged combustion.

1.2 DMB Development History

The development history of the DMB is summarized in Figure 1-3. Initial development of the DMB was conducted at the International Flame Research Foundation (IFRF) under EPA Contract 68-02-0202. This included proof-of-concept tests in a research furnace firing at 8.5×10^6 Btu/hr. Additional development and scale-up tests were conducted at Energy and Environmental Research Corporation (EER) under EPA Contract 68-02-1488. To provide a standard means of evaluating burner performance, two large-scale test facilities were constructed: the Small Watertube Simulator (SWS) and the Large Watertube Simulator (LWS). The SWS was designed to simulate the thermal environment of a small watertube boiler. It had a capacity of 10×10^6 Btu/hr and provided a means of testing burners at moderate scale so that the effects of parameter variations could be evaluated at low cost. The LWS was designed to simulate a large industrial or small utility watertube boiler. The furnace shape was similar to commercial boilers with a hopper bottom, a nose and provision for front-wall firing. The firing capacity of the LWS was 150×10^6 Btu/hr which allowed full-scale burners to be evaluated under conditions simulating large commercial systems.

Six DMB configurations were designed and tested. The designs covered a firing rate range of 10 - 100×10^6 Btu/hr as single burners and a four-burner

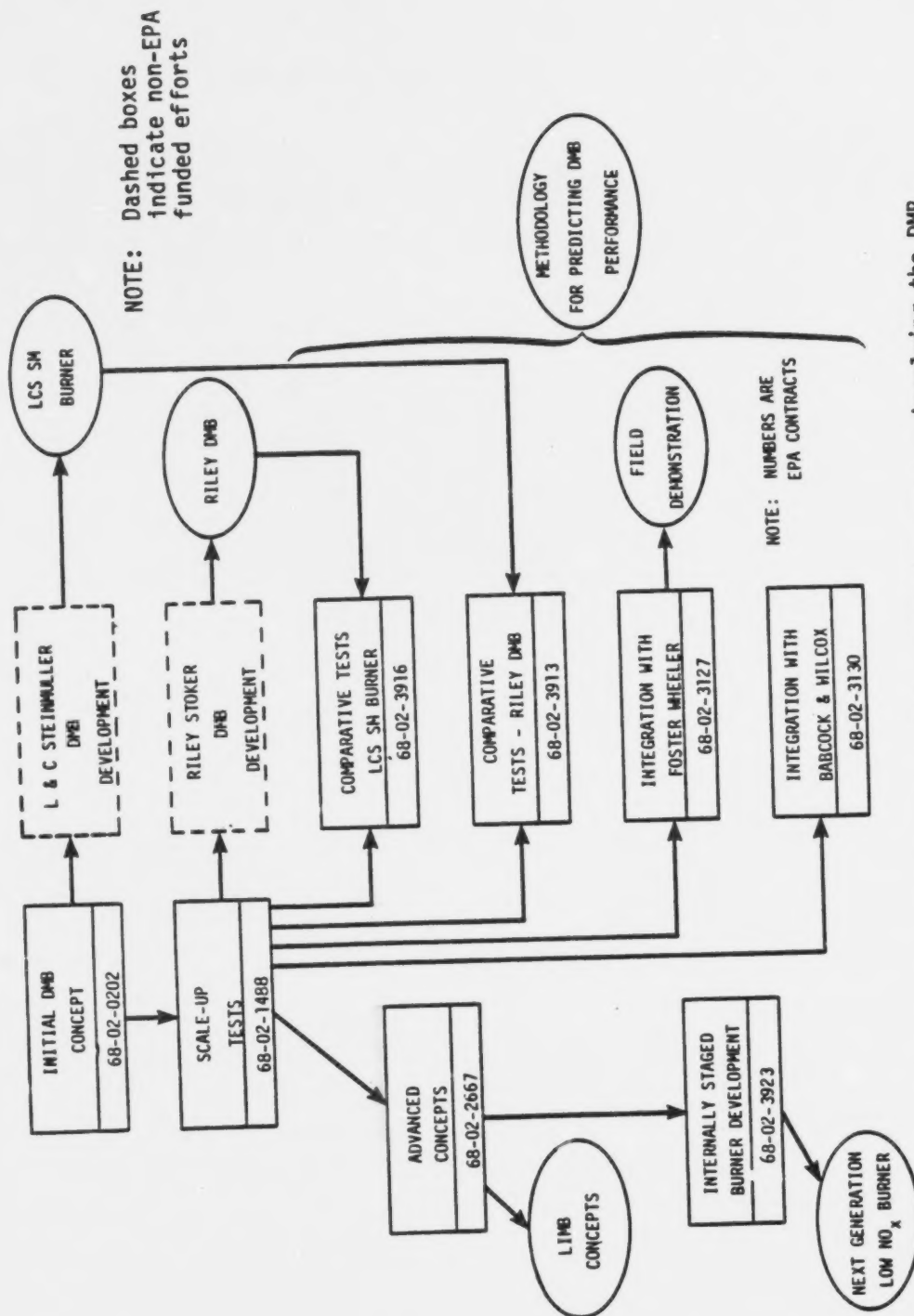


Figure 1-3. EPA research, development and demonstration program involving the DMB.

array. The DMBs were research designs with "flexible" parameters so that the effects of burner design variations on NO_x emissions, flame stability and combustion efficiency could be evaluated. Minimum NO_x emissions for each burner were in the range of 0.1 - 0.2 lb/ 10^6 Btu. The results of the tests were compiled into a set of design criteria which could be used to apply the DMB concept to commercial burners.

At this point, the development divided into two parallel efforts. One focused on advanced concepts of NO_x and SO_x control. In EPA Contract 68-02-2667 the DMB concept was integrated with sorbent injection for SO_x control. The resulting process was termed "Limestone Injected Multi-stage Burner" (LIMB) and considerable development is continuing in this area. In EPA Contract 68-02-3923 advanced burner concepts are being developed to achieve staging without the need for the outboard tertiary air ports of the DMB.

The other effort focused on the further development and commercialization of the DMB. Two EPA field evaluation programs were established. In EPA Contract 68-02-3127 (the subject of this report) the objective was to evaluate the DMB for boiler applications in the 100-500 x 10^3 lb/hr range which is typical of large industrial and small utility boilers. In Contract 68-02-3130, the objective was to evaluate the application of the DMB technology to larger scale utility boilers. These programs were conducted in conjunction with major U.S. burner/boiler manufacturers: Foster Wheeler (FW) for the industrial evaluation and Babcock & Wilcox (B&W) for the utility evaluation. The industrial evaluation has progressed through a field demonstration test. The parallel utility program is still in progress and will proceed through prototype burner testing in a research furnace only. A scaling methodology will be used to project the DMB performance to full-scale utility boilers.

In parallel with this EPA development, two other burner manufacturers have elected to develop DMBs for commercial offerings. Based on the results of the initial IFRF tests, L&C Steinmuller (LCS), a German burner/boiler manufacturer, developed a commercial DMB, the Staged Mixing (SM) Burner. LCS

installed the SM burners in a 700 MW German boiler and demonstrated a 50 percent reduction in NO_x emissions (Leikert and Michelfelder, 1980). The SM burner is now LCS's standard commercial burner offering. Riley Stoker developed a DMB based on the design criteria developed in EPA Contract 68-02-1488 in conjunction with EER.

Table 1-1 summarizes the DMB data base. Additional details on DMB design and performance measured in test facilities, as well as field installations, can be found in Volume 1 of the final report prepared for EPA Contract 68-02-3127.

1.3 Summary of Field Evaluation

The objective of the field evaluation (EPA Contract 68-02-3127) was to evaluate the DMB concept on a commercially operated industrial size boiler. The goal was to attain NO_x emission levels of less than 0.2 lb/10⁶ Btu or as low as possible without adverse affects on boiler operability and durability, thermal efficiency and the emission of other pollutants. The field evaluation involved: (1) translation of the development burner test data in to practical prototype DMBs, (2) verification of the prototype burner performance through testing in a research furnace, (3) construction of field operable DMBs and their installation in a host boiler, (4) evaluation of DMB performance under typical boiler operating conditions, (5) documentation of the results and (6) input to the parallel utility field evaluation (EPA Contract 68-02-3130).

The DMB is intended primarily for new installations. However, it was necessary to conduct the field evaluation by retrofitting an existing boiler. The characteristics of industrial and small utility boilers in the United States were reviewed and several candidate host sites for the field evaluation were selected based on their representativeness, suitability for DMB retrofit and availability. Western Illinois Power Cooperative's Pearl Station Unit 1 was selected as the host site. Table 1-2 summarizes the characteristics of this unit and Figure 1-4 is an elevation view of the boiler. This small utility boiler has characteristics similar to a wide

TABLE 1-1. DMB DATA BASE

BURNER OR COMPONENT MANUFACTURER	BURNER	RESEARCH FACILITY (LWS) TEST	FIELD EVALUATION
FOSTER WHEELER	INTERVANE (PRE-NSPS)	X	FIELD DEMONSTRATION: BURNER REPLACEMENT AT A SMALL UTILITY BOILER
	DMB	X	
BARCOCK AND WILCOX	CIRCULAR (PRE-NSPS)	X	FIELD TEST FIELD TEST
	DUAL REGISTER (NSPS)	X	
	DMB	X	
RILEY STOKER	FLARE (PRE-NSPS)	X	FIELD TEST FIELD TEST
	CCV (PRE-NSPS)	X	
	DMB	X	
L&C STEINMULLER	SM	X	FIELD TEST

TABLE 1-2. HOST BOILER CHARACTERISTICS

Characteristic		Value
<u>Boiler/Furnace</u>		
Boiler Capacity	MCR	215×10^3 lb/hr
	Peak	245×10^3 lb/hr
Furnace Depth		20.6 ft
Furnace Width		16.4 ft
Firing Configuration		Single Wall
Burner Capacity	MCR	69×10^6 Btu/hr
	Peak	80×10^6 Btu/hr
Current Burners	Type	Intervane
	Throat Diameter	24 in.
Burner Array, Wide x High		2 x 2
Burner Spacing:	Horizontal	6.0 ft
	Vertical	6.5 ft
<u>Fuel Supply System</u>		
Coal Type		Bituminous
Mills:	Type	MB
	Number	2
Primary Stoichiometry at:	MCR	16% T.A.
Primary Temperature		155°F
<u>Air Supply System</u>		
Air Heater Type		Regenerative
Design Point Excess Air at:	MCR	18%
Windbox Temperature at:	MCR	510°F
Burner Pressure Drop (Normal)		3.5 in. H ₂ O
Windbox Depth		52 in.

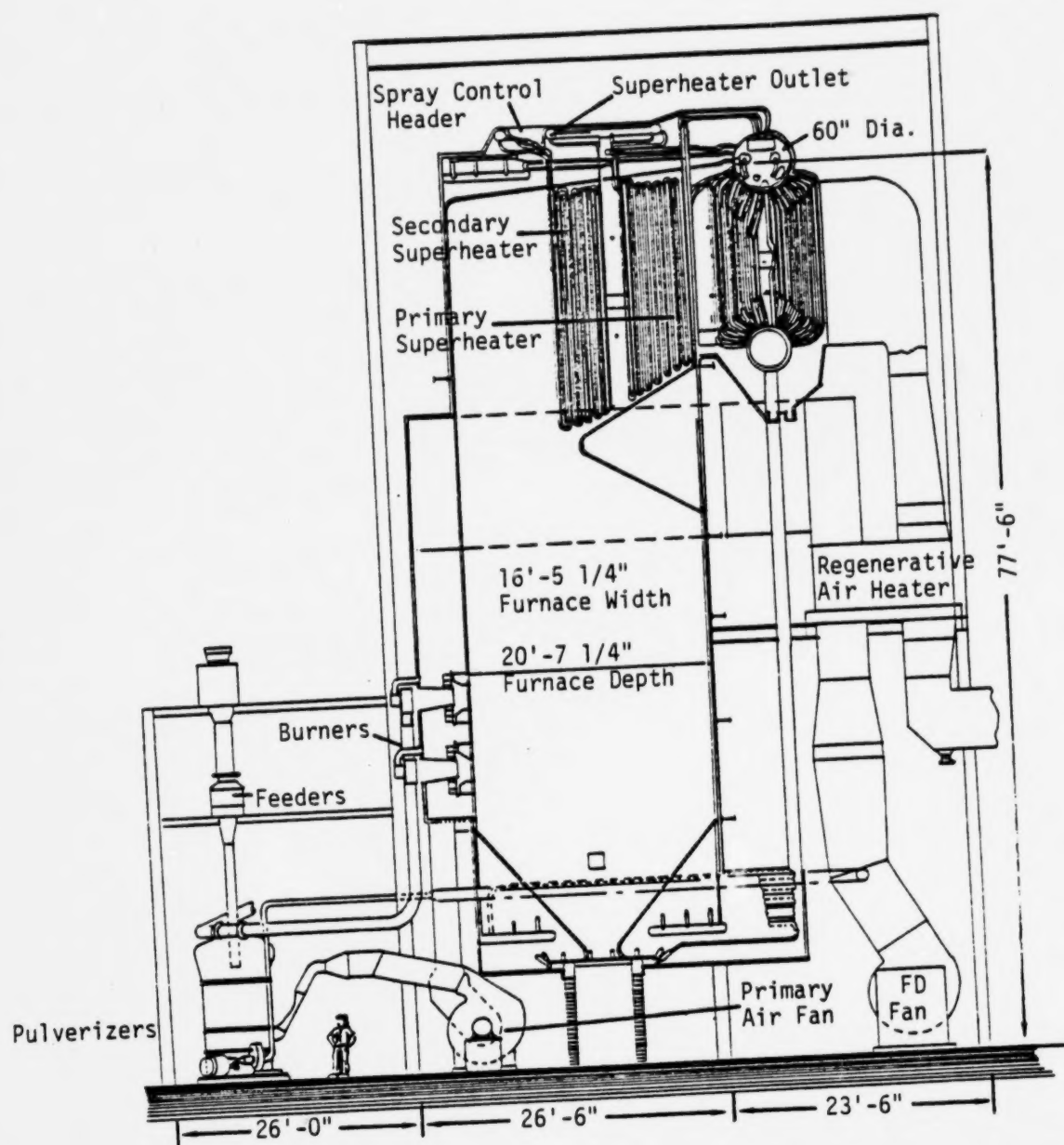


Figure 1-4. Host boiler.

range of medium pressure pre-NSPS boilers. It is equipped with Foster Wheeler's standard pre-NSPS pulverized coal burner, the intervane burner. A baseline test was conducted to evaluate the performance of the host unit over the normal duty cycle. NO_x emissions were approximately $1.0 \text{ lb}/10^6 \text{ Btu}$.

A prototype DMB was designed by integrating the DMB concept with the requirements of the host site and Foster Wheeler burner components. Several versions of the prototype DMB were tested in research facilities to verify performance and confirm that no significant operational problems would occur in the full scale field evaluation. For comparison, an intervane burner was tested also. The DMB design selected for the field evaluation incorporated Foster Wheeler proprietary exit geometry.

Four DMBs were retrofitted to the host boiler using a compromise tertiary air port arrangement. Field tests were conducted over a 17 month period. Generally, the DMB performance met all boiler operational requirements. However, difficulty was experienced in balancing the burners. The data suggest that the burner balancing problems were related to the compromise tertiary air port arrangement. One of the compromises made for the field installation was that of sharing ports between several burners. Subsequently a number of flow modeling studies indicated that burner balancing was very difficult under these conditions. Any differences in flows to the burners would be greatly accentuated by the non-uniform entrainment of the tertiary air. Under balanced conditions, NO_x emissions as low as $0.3 \text{ lb}/10^6 \text{ Btu}$ were measured. Under unbalanced conditions, NO_x emissions were typically $0.5 \text{ lb}/10^6 \text{ Btu}$. Carbon loss increased somewhat with the DMBs but there were no other impacts on normal boiler operation. Extensive tube wall thickness measurements were made during operation with the original burners and the DMBs. No increase in tube wastage was detected.

At the completion of the field evaluation, the host utility elected to retain the DMBs. The unit is currently in operation with the tertiary air ports closed since the utility has no requirement for NO_x emission control.

The key concept of the DMB is the use of tertiary air ports surrounding a circular burner to achieve staging for NO_x emission control without maintaining the entire lower furnace under fuel-rich conditions, as with conventional overfire air port staging. The DMB concept could be achieved with any circular burner simply by directing a portion of the combustion air to the outboard air ports. However, operation of a conventional circular burner, which is designed for unstaged operation, under DMB conditions may produce unacceptable performance. Under DMB conditions, the secondary air flow is approximately half of the air flow for unstaged operation and this may cause a range of undesirable effects such as: flame instability, poor mixing of the primary and secondary air streams leading to high carbon loss, unacceptable flame shape and NO_x emissions higher than for optimum DMB fuel air mixing.

Based on the results of tests in research furnaces and the field evaluation, the "design criteria" for the DMB in Table 2-1 were established. Several design parameters are listed as site dependent (SD) and must be selected based on the requirements of the specific application. The values shown in Table 2-1 produce the best overall balance of flame stability, carbon conversion and emissions in tests of several DMB configurations with firing rate capacities ranging from 10 to 100×10^6 Btu/hr.

Due to site dependent parameters and the range of hardware utilized by the various burner manufacturers, there is no assurance that a burner designed to meet the criteria in Table 2-1 will necessarily perform as expected. These design criteria should be used as an initial design point only. Then the burner should be tested to confirm its performance. In many cases it will be necessary to make some adjustments to the design parameters. The following subsections discuss the design of each DMB component.

TABLE 2-1. DISTRIBUTED-MIXING BURNER DESIGN PARAMETERS

Parameter	Nominal Design Point
<u>Fuel System</u>	
Coal Fineness (% 200 Mesh)	>70
Air/Coal Ratio	Site Dependent
Primary Temperature (°F)	Site Dependent
Primary Stoichiometry (% T.A.)	Site Dependent
Primary Velocity (ft/sec)	75
Primary Swirl	45° Vanes
<u>Secondary Air System</u>	
Temperature (°F)	Site Dependent
Burner Zone Stoichiometry (% T.A.)	50-70
Inner Swirl	Variable
Outer Swirl	Variable
Axial Velocity (ft/sec)	60
Inner/Total Area	0.33
Inner/Total Flow Rate	0.33
<u>Tertiary Air System</u>	
Temperature (°F)	Site Dependent
Swirl	None
Axial Velocity (ft/sec)	50
Angle (degrees)	0
Number	4
Location (radius/throat diameter)	1.8
Divergence (degrees)	0
<u>Exit</u>	
Half Angle (degrees)	25
Length/Diameter	0.4
Setback - Inner Secondary (inches)	0
Setback - Outer Secondary (inches)	0

2.1 Fuel Injector

The primary coal/air mixture from the pulverizer is pneumatically transported to the burners and introduced into the furnace through a coal injector. The air/coal ratio, primary temperature and coal fineness are set by the pulverizer design. The DMB is compatible with the operating characteristics of conventional coal pulverizer systems. Typically, the air/coal ratio will be in the range of 1.2 to 2.5 and the primary temperature will be 160-180°F. Pulverized coal fineness should exceed 70 percent through 200 mesh.

A range of coal injector designs can be utilized in the DMB. The general approach should be to provide the minimum fuel/air mixing rate commensurate with flame stability and length considerations. Rapid fuel/air mixing produces a short, intense and stable flame but it also produces high NO_x emissions due to the premixing that occurs at the base of the flame. Slow fuel/air mixing reduces NO_x emissions but results in a larger flame and in the limit, poor flame stability.

The burner manufacturers utilize either central or annular coal injectors in their commercial burners. DMBs have been designed with both types of coal injectors and there is no clear preference between types. Examples of both design approaches are illustrated in Figures 2-1 and 2-2.

Figure 2-1 shows several central coal injectors incorporating components from several burner manufacturers. In general, these injectors include components to produce a uniform distribution of coal and air across the injector cross section and a method of controlling fuel/air mixing rates within the furnace.

Several approaches to distributing the coal/air across the nozzle cross section are illustrated. The "splash plate" is a hardened and inclined plate located in an elbow. The objective is for coal particles to bounce off the plate uniformly. This splash plate design can be used in conjunction with various types of obstructions in the nozzle to redistribute the coal and

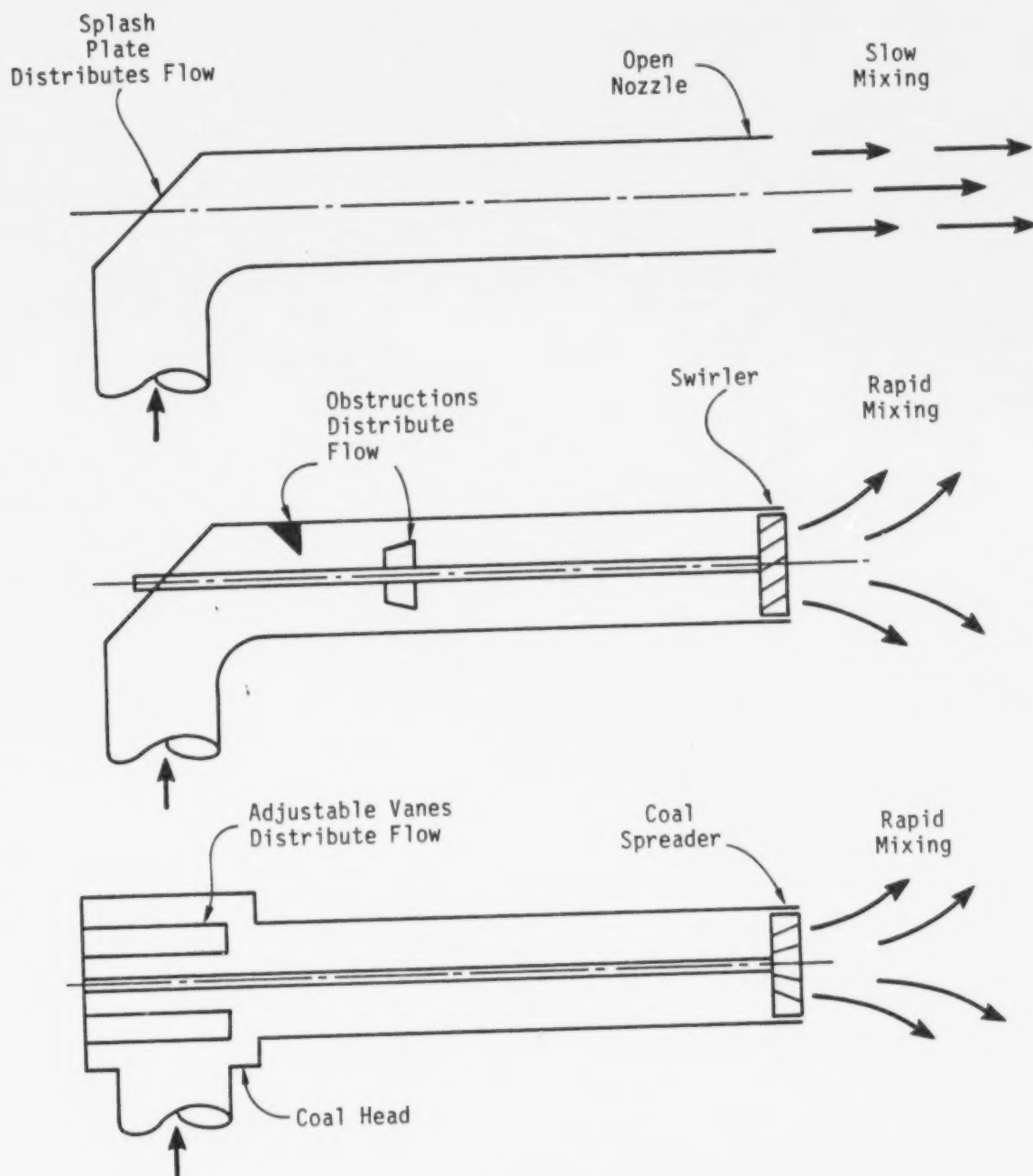


Figure 2-1. Central coal nozzle designs.

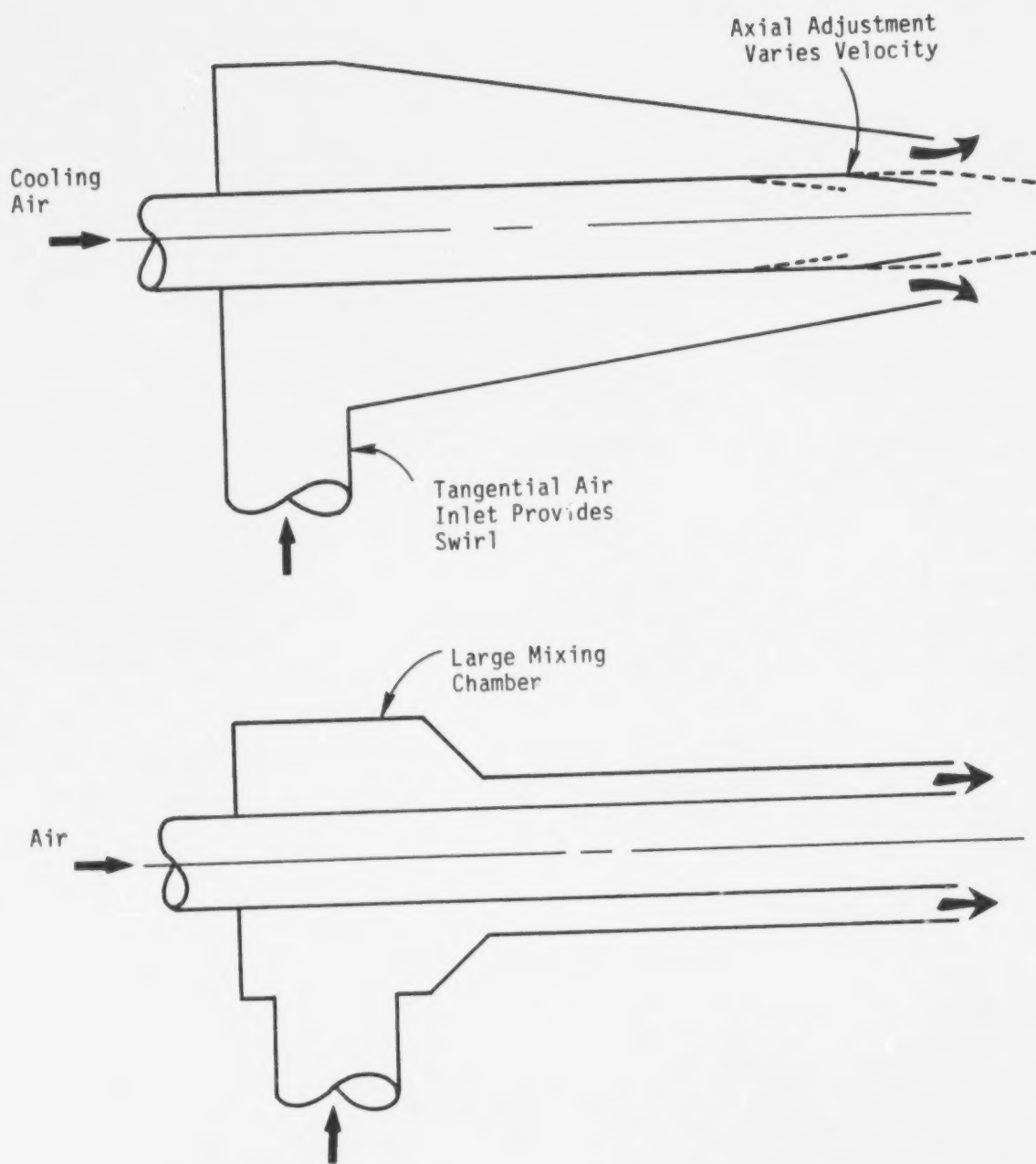


Figure 2-2. Annular coal nozzle designs.

avoid roping. A "coal head" is a chamber of increased cross sectional area with or without adjustable vanes. Turbulent mixing within the coal head helps to insure a uniform distribution of coal in the nozzle.

To control fuel/air mixing rates, various approaches to dispersing the coal into the secondary air stream have been utilized. One limit is a simple open nozzle. This produces a narrow jet of coal which penetrates far into the furnace. Various types of inserts can be placed at the end of the nozzle to increase dispersion. Swirl vanes can be used to divide the coal jet into a discrete number of passages or alternately provide the degree of swirl necessary to increase fuel air mixing. Other designs utilize deflection vanes in the form of a coal spreader.

The initial development DMBs utilized central coal injectors. Tests were conducted with open nozzles and with swirlers of various design. The open coal nozzles produced long flames with low NO_x emissions but flame stability was marginal in some cases. Adding the swirlers shortened the flame and increased flame stability but at the expense of slightly higher NO_x emissions. The best overall performance was obtained with a swirler type coal spreader with 45° vane angles. In future DMB designs with central coal injectors, the primary velocity should be set at about 75 ft/sec and alternate coal spreader designs should be tested and optimized to balance flame shape, flame stability and NO_x emissions.

Figure 2-2 illustrates two annular coal injector designs. In one design, the coal enters the nozzle tangentially through an inlet scroll. This distributes the coal around the nozzle circumference. The nozzle shown includes an adjustable inner barrel which varies the open area and hence the primary velocity. Since the coal enters the scroll tangentially, some swirl probably exists at the nozzle exit. In the other annular nozzle design, the coal and air enter a large mixing chamber upstream of the nozzle, similar to the coal head, to provide a uniform distribution over the nozzle cross section. No swirl is provided. The coal and air exit the nozzle axially.

In some annular nozzle designs, only a small quantity of cooling air is provided to the central passage. In others, a substantial portion of the combustion air may be provided along the burner centerline. Thus, the rate of fuel/air mixing can vary substantially.

The prototype DMBs and the DMBs for the field evaluation utilized Foster Wheeler's annular coal nozzle similar in concept to the tangential inlet configuration in Figure 2-2. The nominal primary velocity was 75 ft/sec. Flame characteristics could be varied substantially by adjusting the primary velocity.

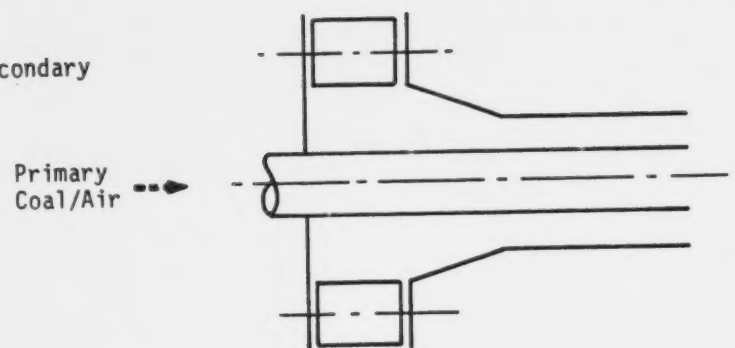
2.2 Secondary Air System

The secondary air system provides an annulus of secondary combustion air around the coal injector. The secondary air is normally supplied from a windbox at about 600°F. The specific temperature is established by air heater design and is not critical to DMB performance.

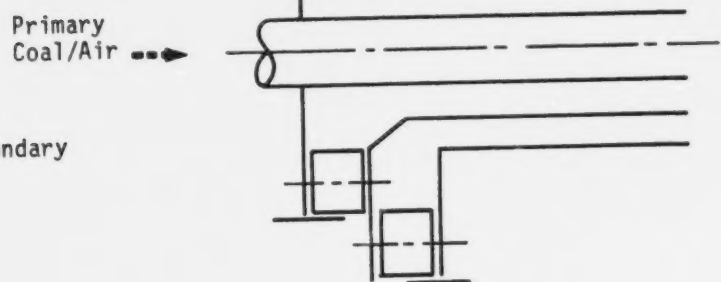
It is preferred to provide secondary air to the DMB through two concentric passages each with independent flow rate and swirl control. This provides the high degree of control necessary to optimize DMB performance by minimizing fuel/air mixing rate commensurate with flame stability and shape considerations. However, DMBs with single and dual secondary air passages have been constructed and tested successfully. A secondary velocity should be selected to produce controlled fuel/air mixing. A velocity of 60 ft/sec, slightly less than the primary velocity of 75 ft/sec, is recommended.

The burner manufacturers utilize various combinations of registers, swirl vanes and sliding components to control secondary air in conventional burners. These can be used directly in the DMB. Figure 2-3 illustrates several approaches to controlling secondary air flow using these components. Figure 2-3a illustrates a conventional single secondary with a single register as the air flow control device. This configuration is typical of pre-NSPS burners. The register performs three functions: flow control, swirl control and flow shutoff (burner out of service). With the burner in

A. Single Secondary

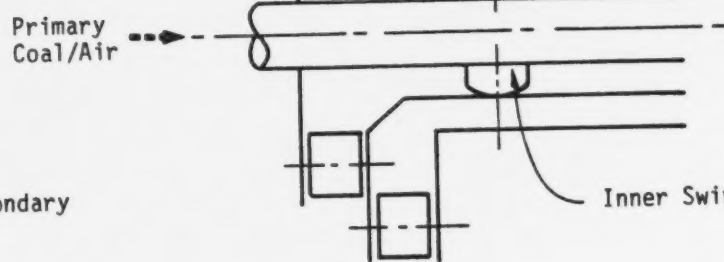


Inner Sleeve (Flow)
 Inner Register (Swirl)
 Outer Sleeve (Flow)
 Outer Register (Swirl)



B. Dual Secondary

Inner Register (Flow)
 Outer Register Flow/Swirl



C. Dual Secondary

Inner Swirl Vanes

Figure 2-3. Secondary air designs.

service, flow and swirl are controlled together - opening the register decreases swirl but increases the air flow rate simultaneously.

Figure 2-3b shows a dual secondary system with registers and sliding sleeves on each passage. The registers may be closed for flow shutoff and are the primary element controlling swirl when the burner is in service. The sliding sleeves provide additional restrictions so that the air flow rate may be controlled independent of the swirl produced by the register. Figure 2-3c is a dual secondary system with a single register for combined flow/swirl control on the outer passage and a register plus swirl vanes on the inner passage. The registers provide for flow shutoff as in Case B. In the outer passage, the flow rate and swirl are linked by the register position. In the inner passage, the swirl vanes control the swirl while the register controls the flow rate independently.

The total secondary air flow rate is a key variable since it established the burner zone stoichiometry. The burner zone stoichiometry should be as low as possible commensurate with flame stability and combustion efficiency constraints. The effect of burner zone stoichiometry is illustrated in Figure 2-4. These trends are typical of those measured in the research furnace and field evaluation of the DMB.

Conventional burners have no tertiary air ports; all of the combustion air passes through the burner throat and the overall stoichiometry is in the range of 120 percent TA. As the air is diverted from the burner throat to the tertiary air ports, the NO_x emissions decrease approximately linearly. This suggests that the DMB should be operated at the lowest possible burner zone stoichiometry. However, as the burner zone stoichiometry decreases, combustion efficiency degrades as evidenced by increasing CO emissions and carbon in the fly ash. Typically, the decrease in combustion efficiency is zero or slight down to a burner zone stoichiometry of about 70 percent TA. At lower burner zone stoichiometries, CO emissions and carbon loss increase substantially and in some burners, a flame stability limit is reached. Thus, the best overall operating condition for the DMB is the lowest possible burner zone stoichiometry commensurate with these constraints.

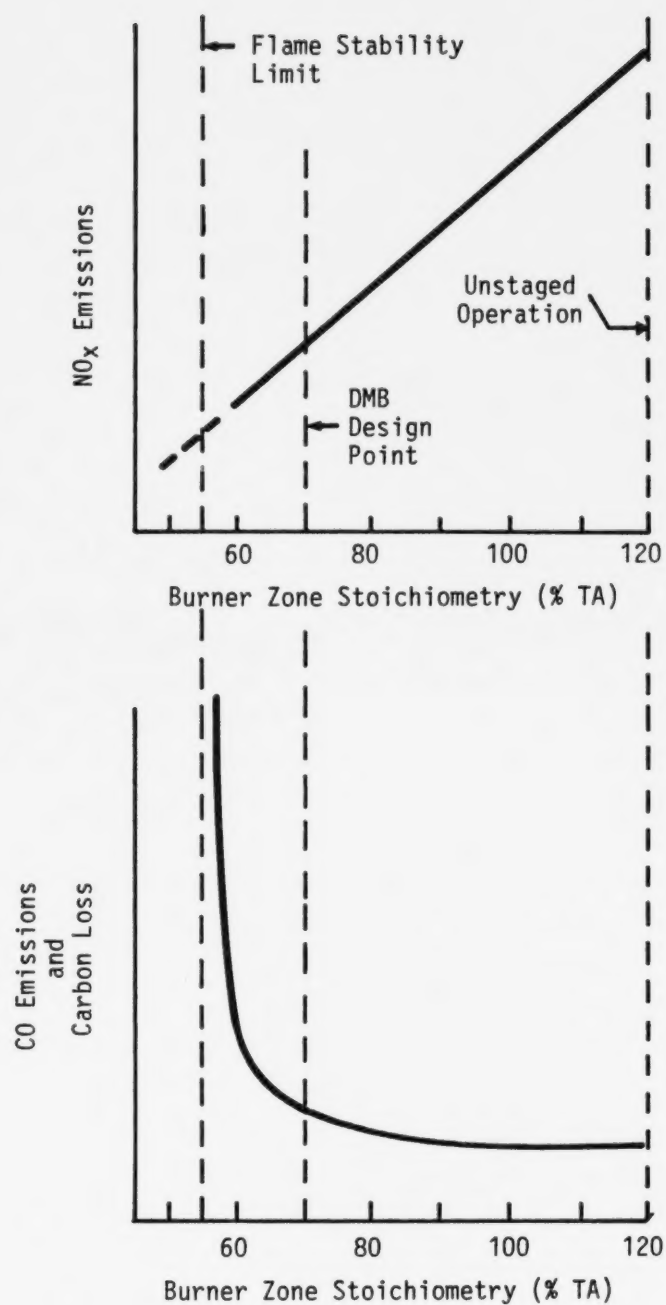


Figure 2-4. Effect of burner zone stoichiometry on DMB performance.

The stoichiometries specified above are typical but depend to some extent on the details of the DMB design as well as operational settings. Thus, the DMB should be designed to operate at a burner zone stoichiometry of 70 percent theoretical air but the optimum operating stoichiometry must be determined through testing.

2.3 Burner Exit

The burner exit is the opening of the burner connected through the furnace wall. The initial development DMBs utilized a long refractory exit with a length to diameter ratio of 1.0. This exit design was intended to provide improved flame stability with low secondary air velocities. Subsequent tests conducted with the prototype DMBs included a range of exit lengths. A length to diameter ratio of 0.4 was finally selected based on the best balance of overall performance.

2.4 Tertiary Air System

The tertiary air system is the only DMB component located outboard of the burner throat. Tertiary air would normally be supplied from the windbox at a temperature of about 600°F utilizing suitable control dampers etc. Any control system design which provides reliable control and metering of the tertiary air would be acceptable.

The tertiary air ports should be located uniformly around the burner throat at a radial distance of about two throat diameters from the burner centerline. Four ports per burner are recommended with an axial velocity of 50 ft/sec which is slightly less than the secondary air velocity (60 ft/sec).

The tertiary air port location criterion implies a minimum burner to burner spacing. For closely spaced burners, the port locations must be compromised. Either the ports must be located closer to the burner centerline or ports from adjacent burners could be combined. The results of the field evaluation suggest that these approaches do not affect NO_x

emissions per se; however, it may be difficult to balance the burners. This is discussed in Section 3.0.

The Distributed Mixing Burner (DMB) concept can be applied to both existing and new utility boiler designs for the purpose of controlling NO_x emissions. The field evaluation of the DMB during this program has provided the information necessary to determine the applicability to both design situations. As with all new technologies, a number of concerns arise that must be addressed. This is certainly true for the DMB technology. Some of those concerns are unique to the retrofit situation while others are common to all boiler applications. The following Subsection 3.1 discusses the new boiler application while Subsection 3.2 addresses the retrofit case.

The retrofit costs of this technology are so site-specific that even a general projection of those costs would be misleading. The concerns outlined in Subsection 3.2 should be evaluated for each prospective site to ultimately determine the suitability of a DMB retrofit.

The cost differential associated with applying the DMB technology to new boiler designs, however, can be presented in a useful manner. Using a modern NSPS utility boiler design as the base case, cost implications of designing the same boiler with the DMB firing system can be estimated with reasonable accuracy. Those cost differentials should enable users, architect/engineers, and manufacturers to assess the relative benefits of the DMB technology.

3.1 Applicability of the DMB Concept to New Utility Boiler Designs

The application of the Distributed Mixing Burner concept to new boiler designs, the primary development goal of this program, is not nearly as complex as the retrofit situations. This subsection discusses the DMB application to new boilers with emphasis on the differences compared to a conventional NSPS boiler design. The following subsection details the study approach. The remainder of the subsections discuss the boiler design and operating changes and cost impacts.

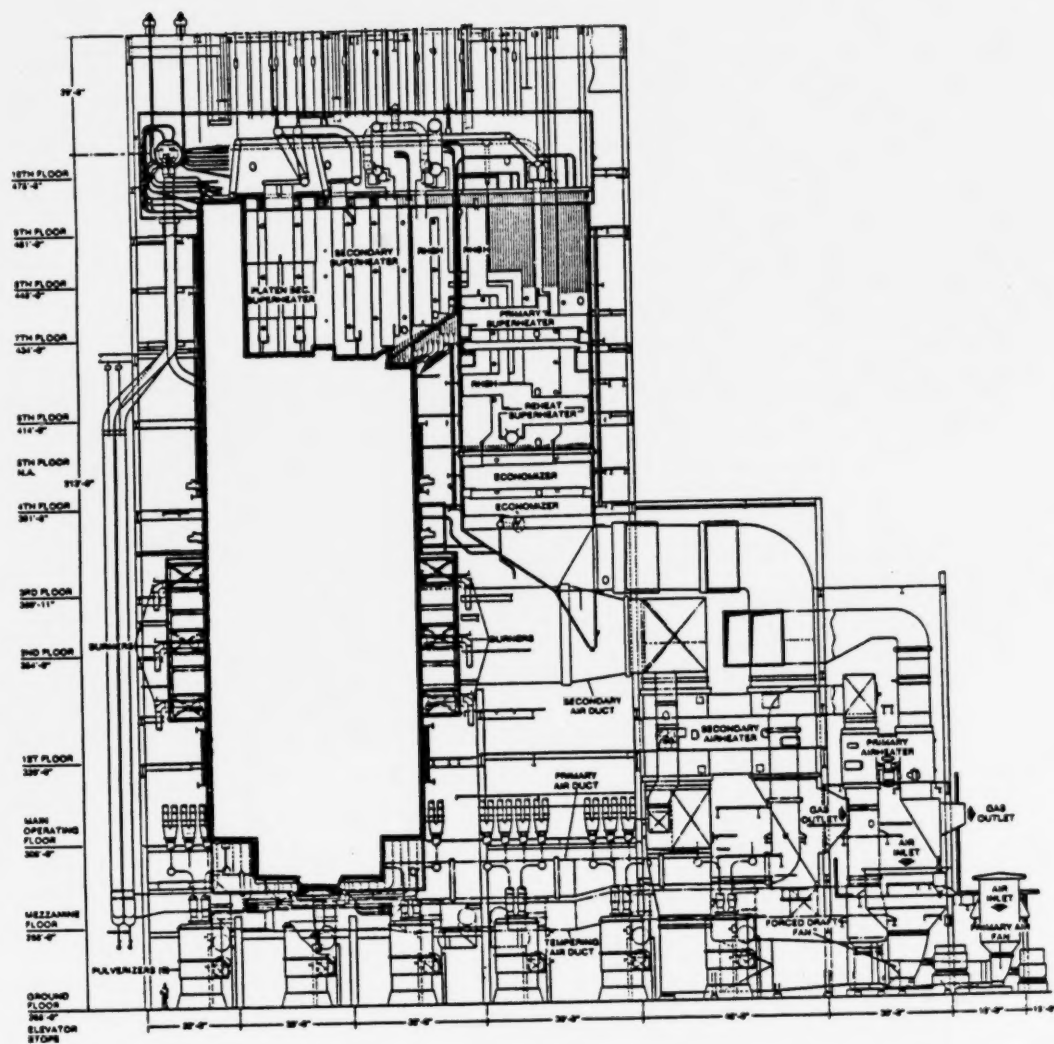
3.1.1 Study Approach

The approach taken for assessing the applicability and associated costs of applying the DMB concept to new utility designs was to compare a DMB-equipped boiler to its conventional NSPS equivalent. The majority of NSPS boilers sold by domestic manufacturers range in size from 450 - 750 MWe maximum continuous rated capacity. A conventional NSPS boiler equipped with commercially-available "low-NO_x" burners was selected as the "base" case. Using the DMB design criteria presented in Subsection 2.0, a DMB firing system was designed for the same boiler. The cost impacts of the DMB system were then estimated and reported on a cost differential basis from the conventional design.

The "base" NSPS boiler selected for comparison is a 625 MWe, opposed-fired, natural circulation boiler presently in operation in the Northeastern United States. A sectional side view of the boiler is shown in Figure 3-1. It is capable of continuously producing 4,750,000 lb/hr of steam at 2620 psig and 1005°F.

The boiler is arranged with a water cooled dry-bottom furnace, superheater, reheater, economizer, and air preheater. The firing system is designed to meet an NO_x emission limit of 0.7 lb/10⁶ Btu and includes 48 "low-NO_x burners" which are supplied with pulverized bituminous coal from six pulverizers. The firing arrangement includes three elevations of burners, eight burners wide, on both the front and rear walls of the furnace. Heated secondary air is distributed to the burners utilizing a compartmented windbox which provides each elevation of burners independent air flow measurement and control.

The cost impacts of applying the DMB firing system, described in Subsection 3.1.2, are evaluated as a percent change from the base cost and are summarized in Subsection 3.1.6. The impact of the DMB design parameters on furnace sizing is discussed in the following Subsection, 3.1.3. The most significant modifications as a result of the DMB application are to the



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Figure 3-1. Base 625 MW_e conventional boiler design.

firing wall panel construction and to the control system. These modifications are discussed in Subsections 3.1.4 and 3.1.5, respectively.

3.1.2 DMB Design

The conventional burners were designed to meet a fuel input capacity of 112×10^6 Btu/hr. As noted in the conventional boiler description, the unit was equipped with 48 burners. A significant adjustment that will have to be made when applying DMBs to new boilers is the reduction in the number of burners. By reducing the number of burners, and at the same time increasing the fuel input/burner, a boiler furnace sized in the conventional manner will not have to be changed for the DMB firing system. This is a much more cost effective approach than trying to maintain the same number of DMBs and changing the furnace dimensions to accommodate them. Additional space between burner throats is required by the DMB design to enable the tertiary ports to be located a sufficient distance from each throat to achieve reasonable NO_x emission reductions. Subsections 3.1.3 and 3.1.4 will discuss the furnace size criteria and the burner arrangement in the firing walls in much more detail.

For the above reasons, the DMB design for the cost analysis includes only 36 burners with a capacity of 149×10^6 Btu/hr each. The pulverized coal output of each pulverizer is simply split into six rather than eight streams. The total fuel input to the boiler remains constant as no change in boiler efficiency is predicted as a result of the firing system change.

Figures 3-2 and 3-3 show artist views of the conventional low- NO_x burner and of the distributed mixing burner as they appear from inside the boiler furnace. Note that the burner internals are similar for this study, as though both burners were built by the same manufacturer.

The major windbox change required is also illustrated in Figure 3-3. That change is the addition of a partition that divides the combustion air flow between the burner components and the tertiary air ports. The vertical partition is similar in construction to the horizontal plates that separate

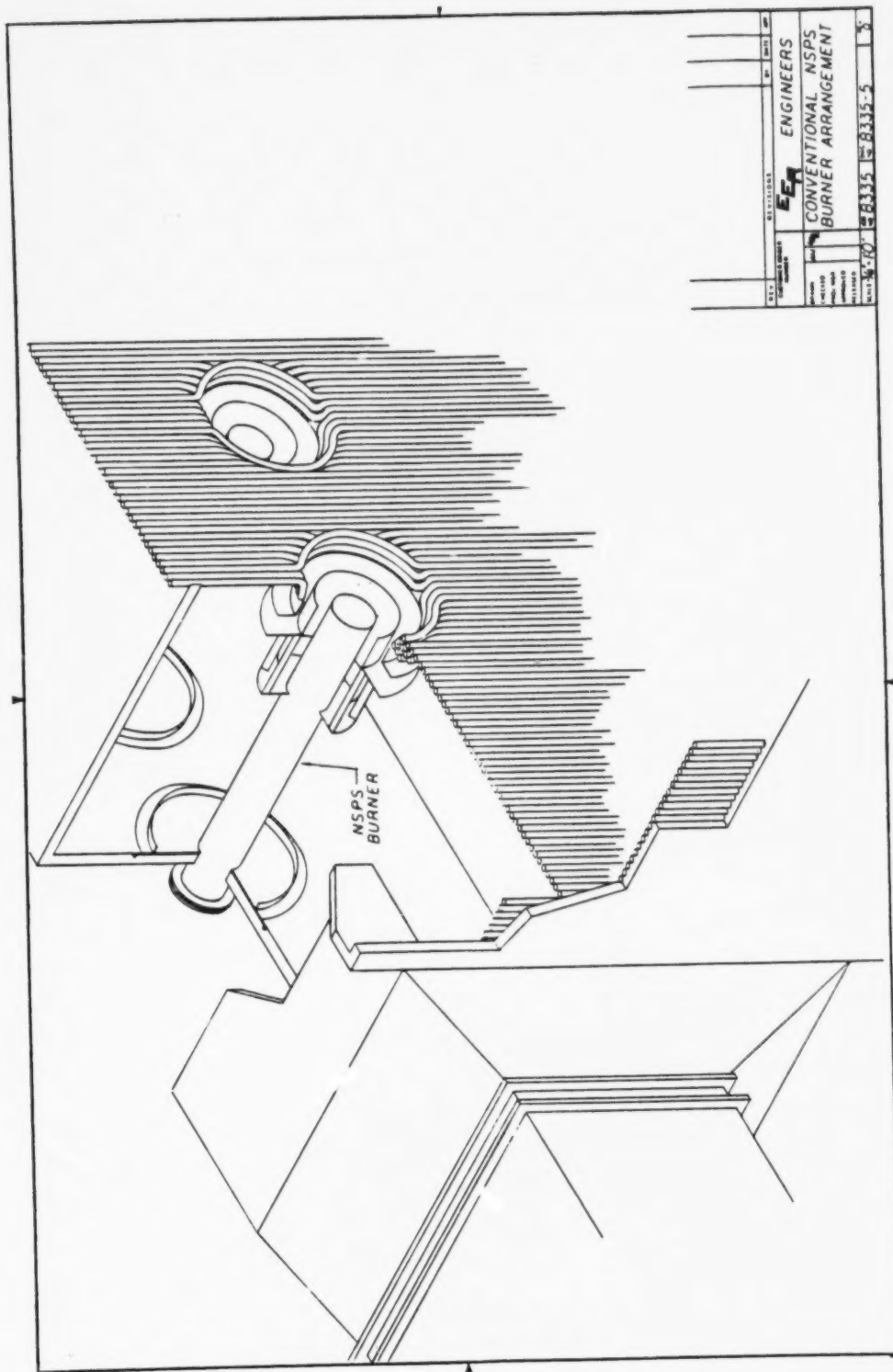


Figure 3-2. Conventional NSPS burner arrangement.

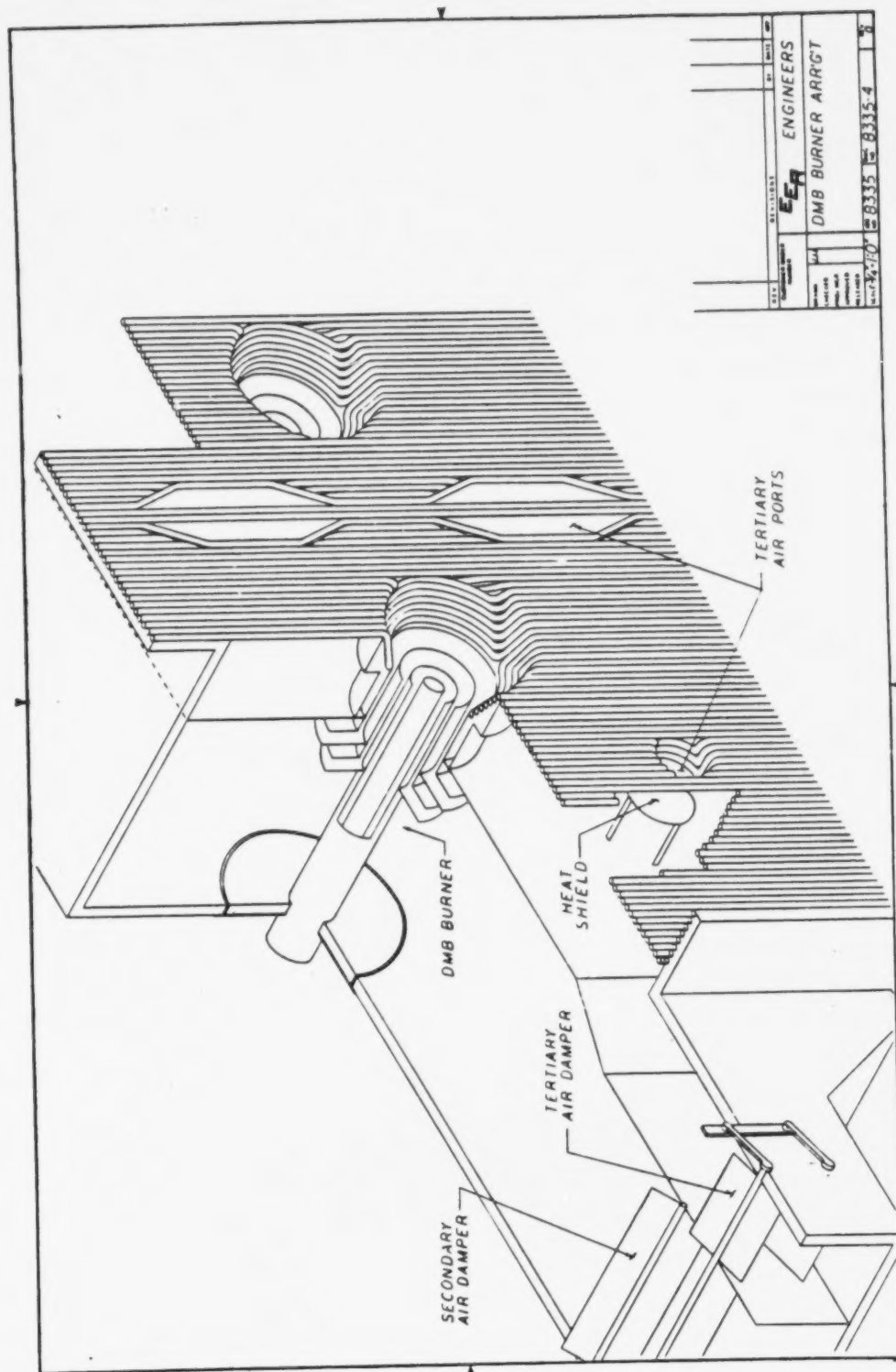


Figure 3-3. DMB burner arrangement.

the windbox into horizontal compartments. This compartmented windbox design allows independent air flow measurement and control for each elevation of burners. Since each elevation is also supplied fuel from an individual pulverizer with fuel flow measurement, the fuel/air ratio can be carefully controlled. The DMB firing system requires the addition of dampers to control the tertiary port air flow. Subsection 3.1.5, Operation and Control, will discuss the damper operation in detail.

All mechanical design constraints that apply to any equipment placed in the thermal environment of a utility boiler windbox would apply to the DMB. The maximum temperature of the burner materials, thermal stresses, differential thermal expansion, and protection from the furnace radiation are all important in the detailed design of the burner. For the purposes of this evaluation, there are no special design constraints associated with the DMB that are not presently applied to conventional firing systems.

The major design parameters, unique to the DMB, that are significantly different from conventional burners are those associated with the tertiary air ports. These ports, also illustrated in Figure 3-3, enable the burner to be operated at low burner zone stoichiometries to minimize NO_x emissions. For multiple burner applications, it is necessary to share tertiary port locations horizontally between burners. This is an important criteria to prevent furnace width from changing drastically and to reduce the number of openings in the furnace walls. These concepts will be discussed further in the following subsections. For the present, note that the ports are shared horizontally but not vertically. This maintains the independent firing control of each burner elevation/pulverizer "group".

The detailed design of the port opening is not critical either for the purposes of the economic evaluation or the performance of the DMB. Each boiler manufacturer will undoubtedly address the port design in a slightly different manner. A significant design consideration will be to minimize the radiant heat transfer to windbox components. The shared ports in particular are fairly large openings to that could expose large portions of windbox partitions and support members to direct flame radiation. This study assumes

that protection will be afforded by a combination of the boiler wall tubes bent to form the opening, polished stainless steel "shine" plates to redirect much of the radiation back into the furnace, and constant secondary air flow through the port.

The port design illustrated in Figure 3-3 shows the shared tertiary ports were formed with two straight tubes through the center of the port. These tubes may tend to split the flow slightly and promote uniform tertiary air mixing between the burners.

The mechanical design details of internal burner components may vary significantly from manufacturer to manufacturer and still provide acceptable emissions reduction performance as long as the basic DMB tertiary port design criteria are met. Similar to the port design, those parameters can be met with a variety of different burner designs, materials of construction, fabrication techniques, etc. Each manufacturer can develop the specific detailed mechanical design with which he is most comfortable. The cost study assumed that the burner internals for a DMB will cost the same as the internals of a conventional low- NO_x burner of equivalent throat size.

The various design approaches for burner internal parts will result in operational characteristics varying from burner to burner. Flame shape, stability, turndown capability, and pressure drop will all be affected by each manufacturer's specific design.

3.1.3 Furnace Size

Boiler furnace sizing is primarily a function of coal quality and the past experience of the boiler designer with the design fuel. Two parameters used for describing furnace size are the Plan Area Heat Release Rate (PAHRR) and the Furnace Liberation Rate (FLR). Both parameters are used to define the early conceptual design of a boiler furnace. The exact size is finally determined by heat transfer calculations and certain manufacturing constraints. Both parameters, as well as the Burner Zone Liberation Rate (BZLR) discussed earlier, are widely used as a means of relating the

combustion and emissions performance of one boiler to another. The BZLR parameter was developed to relate NO_x emissions performance to a parameter that was proportional to the flame zone bulk temperature. It is used primarily to determine burner spacing, and therefore burner zone height, in the furnace. All three parameters are used iteratively until an optimum furnace size is developed that combines satisfactory performance with minimum material, fabrication, erection, and operating costs.

The base boiler selected for this study was designed for a severe slagging coal and, consequently, has a fairly large furnace volume to provide lower flue gas temperatures entering the convective heat transfer surfaces of the boiler. The lower gas temperatures discourage the formation of troublesome ash deposits that are anticipated from the severe slagging classification of the design coal. The PAHRR and FLR parameters usually decrease with increasing furnace size and are relatively low for the base boiler. It is important to understand that, while the base boiler selected may not be perfectly representative of the existing population, it is quite representative of the boilers which will be designed and put into service over the next few decades. The trend toward furnace designs with lower PAHRR and FLR considerations over the past 15 years should continue into the foreseeable future. This is largely due to the lower quality coal sources that are being exploited and which will become the dominant sources of supply for new steam generation capacity.

Another criteria for furnace sizing that normally only applies to smaller ($<150 \text{ MW}_e$) boilers is that of burner flame length. Particularly with single wall fired designs, the minimum furnace depth must be slightly longer than the burner flame length. Most conventional low- NO_x burner designs with capacities greater than $100 \times 10^6 \text{ Btu/hr}$ require a furnace depth of at least 25 feet. The unique fuel/air mixing characteristics of the DMB will require, in most cases for optimum emissions reduction, at least as much furnace depth to minimize rear furnace wall flame impingement. If maximum NO_x emissions reduction is not necessary, the DMB flame length can be reduced to suit a particular furnace depth constraint. Flame impingement must be avoided due

to the probability of the tube overheating, ash deposition, and increased carbon loss which usually occur as a result.

The Plan Area Heat Release Rate is calculated by dividing the heat input of the furnace at maximum continuous rated capacity by the furnace plan cross-sectional area. That plan area is usually based on the area of a horizontal plane through the burner zone. For the base boiler design, the furnace dimensions at the burner zone are 73 ft. x 51 ft. or 3723 sq ft. and the total heat input is approximately 5376×10^6 Btu/hr. The PAHHR is therefore 1.44×10^6 Btu/hr-ft². The majority of NSPS boilers are designed with a PAHHR in the range of 1.4 to 2.0×10^6 Btu/hr-ft². As the slagging tendencies of the design fuel become more severe, the furnace PAHHR will tend to move toward the lower end of the existing range. As fuel quality declines in the future, the "representative" range for PAHHR will also decline.

In a similar manner, the Furnace Liberation Rate decreases as the coal quality, and therefore, furnace size increases. For the conventional boiler design selected, the furnace volume is approximately 490,000 ft³. The FLR is calculated by dividing the heat input, 5376×10^6 Btu/hr, by the furnace volume. The base boiler FLR is approximately 10,970 Btu/hr-ft³ which, again, is toward the lower end of the design range of 10,000 - 30,000 Btu/hr-ft³. In similar fashion to the PAHHR, as the slagging tendencies of the design fuel become more severe, the FLR will tend to move toward the lower end of the existing range. As fuel quality declines in the future, the "representative" range for FLR will also decline.

The minimum space required between a burner throat and a furnace sidewall is also a function of burner performance and coal quality. Slagging can become a serious problem on sidewalls that are too close to a burner which, in turn, can lead to tube failures. Mechanical connections to the boiler corners, limiting the heat flux to the sidewall tubes, and other factors all enter into the determination of the minimum burner/sidewall spacing criteria. Conventional boiler design philosophy has normally set the spacing restriction between 5 and 15 feet. Figure 3-4 illustrates a recommended relation between burner heat input and sidewall spacing. The

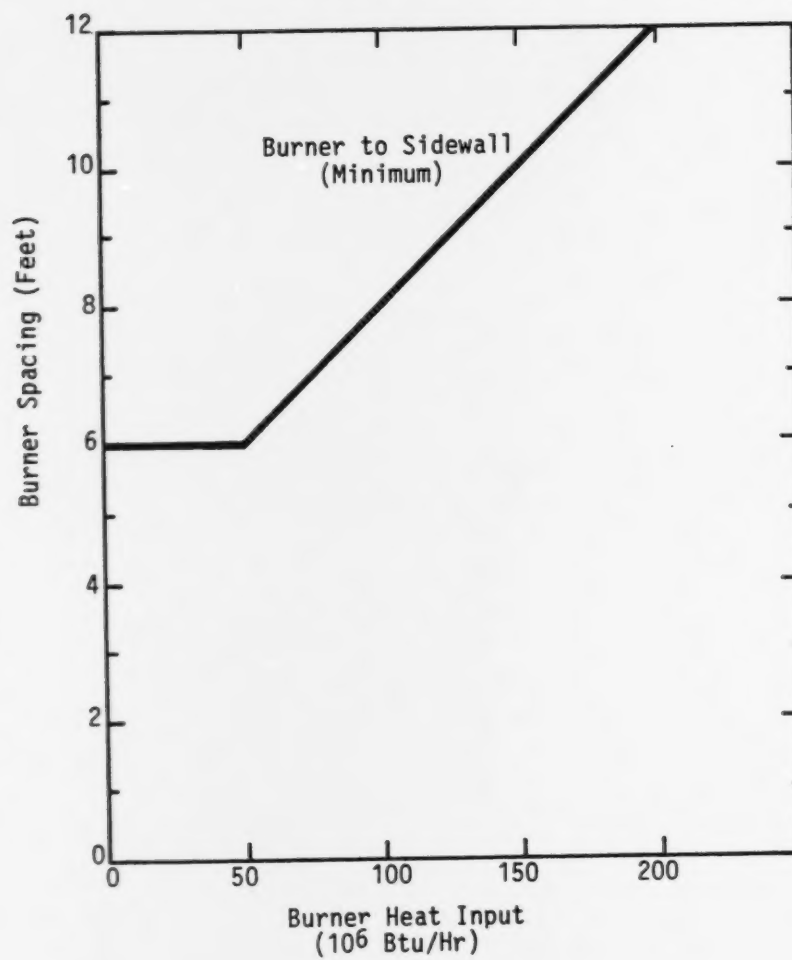


Figure 3-4. DMB boiler burner to sidewall spacing.

design of the DMB should not impact any of these spacing criteria in a negative manner. Actually, since the tertiary air ports are adjacent to the sidewalls, many of the gas-side problems normally encountered should be minimized. A 10 ft. minimum sidewall spacing was assumed for the DMB in the new boiler application.

The application of the DMB to new boiler designs should not significantly impact conventional furnace sizing procedures. In the majority of new boilers designed in the future, conventional furnace sizing criteria, based on predicted coal quality effects, should be applied to boilers equipped with DMB firing systems. Some minor modifications to the furnace size may be appropriate based on the burner/tertiary port arrangement on each firing wall. Figure 3-5 can be used as a guide for selecting the size and number of DMBs for each firing wall. The figure assumes that the DMB design parameters are followed and that the tertiary air ports are shared horizontally between burners.

3.1.4 Firing Wall Arrangement

The design of the firing wall has been the object of much concern and attention during the development of the DMB concept. The necessity of the tertiary air ports, requiring a substantial increase in the number of openings in the firing walls, has always been considered detrimental to the concept application. While the DMB retrofit at WIPCO's Pearl Station seemed to support that concern, the new boiler application does not. The extreme number of constraints imposed by the retrofit situation do not apply in the new boiler design case.

The firing wall arrangement is determined by DMB throat size, tertiary port design, burner spacing, and spacing between the furnace side walls and adjacent burners. The design approach, and possible alternatives, of each are addressed in further detail below before presenting the arrangement selected for the DMB cost analysis. Comments referring to "pre-NSPS" and "NSPS" burners are intended to represent generic burner design practices used

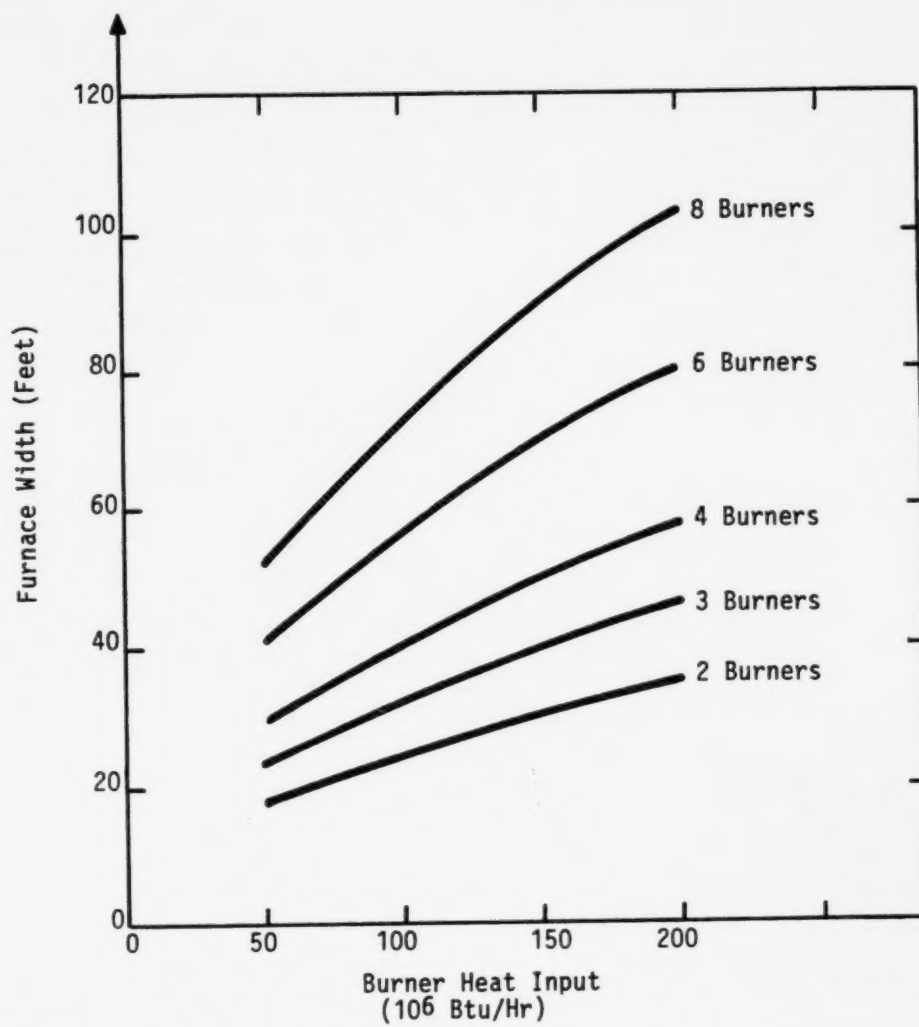


Figure 3-5. DMB boiler furnace width.

by the burner supply industry before and after promulgation of the New Source Performance Standards in 1972.

Throat Design

The throat opening diameter, calculated per the DMB design criteria, varies with the burner heat input. Figure 3-6 illustrates the relative throat diameters of typical pre-NSPS, conventional NSPS, and DMB burner designs as a function of heat input. Even though the DMB throat velocity is lower than either of the other burner types, the reduced secondary air flow required to maintain a 70 percent burner zone stoichiometry results in a smaller throat opening. These dimensions are approximate. The specific burner designs employed by some burner manufacturers such as the core air passage in Foster Wheeler burners may increase throat diameter for the same primary and secondary velocities.

Tertiary Port Design

The design of the tertiary air ports includes the port size, shape, and radial distance from the burner throat. While the port flow area and radial distance are defined by the DMB design parameters, the final port design can vary widely depending on the strategy used for determining the total number of ports and for controlling the air flow to the ports.

Ideally, the port design is a simple circular wall opening with four individual ports per burner. Practically, however, the expense incurred by accommodating that approach is prohibitive. The large number of furnace wall tubes that must be bent to form the ports and the additional furnace width required makes this approach very unattractive. To minimize the furnace width impact of the DMB application, it is desirable to share ports horizontally between burners. To minimize the number of tubes bent, the port shape should be lengthened parallel to the orientation of the furnace wall tubes. In most domestic applications where the wall tubes are oriented vertically, the "ideal" round port should become rectangular in shape with the longer dimension of the rectangle oriented vertically also.

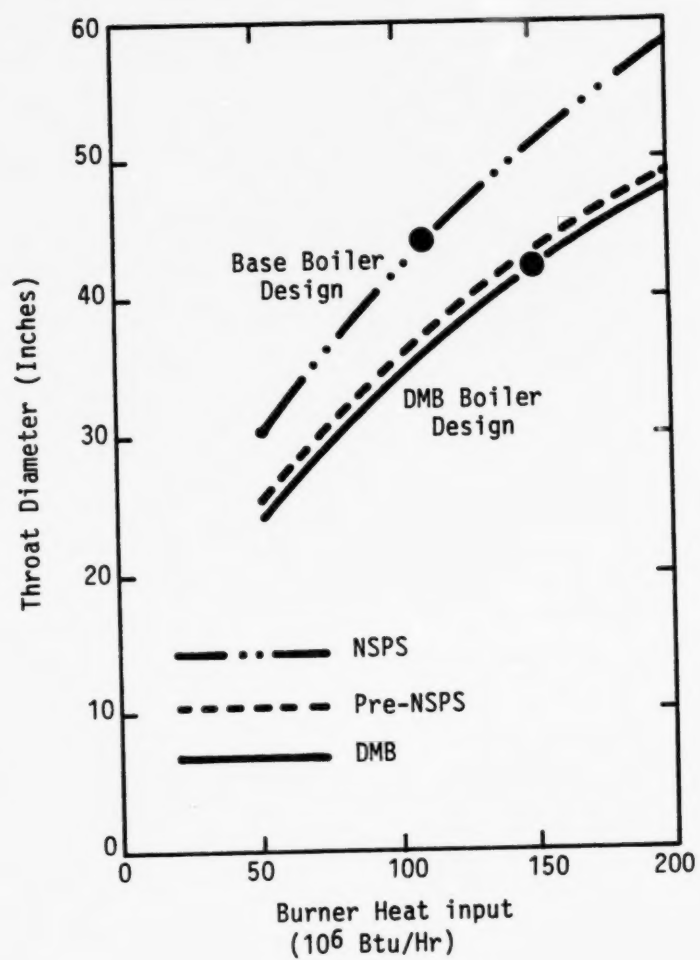


Figure 3-6. Relative burner throat diameters.

Individual ports for every burner requires the maximum number of port openings in the firing wall. The minimum number of openings are required if ports are "shared" both vertically and horizontally (similar to the WIPCO arrangement). Shared ports refer to ports designed to provide tertiary air to more than one burner. Depending on the location of the ports with respect to the burner throats, and whether it is shared in more than one direction, a port could be shared by up to four burners. However, to minimize burner balancing problems, port sharing should be minimized.

In order to minimize the number of wall tubes that must be bent to form the tertiary port openings, sharing ports horizontally is highly desirable. Since the load-bearing capability of a tube is reduced once it is bent, having multiple ports in the vertical direction can be tolerated. In addition, since virtually all firing control systems are based on horizontal groups of burners (firing elevations), horizontally shared port air flows can be easily controlled in conjunction with their respective burners (discussed further in Subsection 3.1.5). Based on these two important considerations, the DMB firing wall arrangement utilized for the economic analysis includes horizontally shared tertiary air ports.

Burner Spacing

The space between burners adjacent to one another in the firing wall is largely determined by the tertiary port location criteria (horizontally) and by burner zone liberation rate (BZLR) furnace criteria (vertically). Figure 3-7 illustrates the horizontal burner spacing required (throat centerline to centerline) for burners as a function of heat input. The correlation for both individual and horizontally shared tertiary air ports is shown. The minimum vertical burner spacing will be the same unless BZLR criteria require wider spacing which results in increasing the burner zone volume and therefore reducing the BZLR.

Figures 3-8 and 3-9 illustrate the burner throat and tertiary air port openings on one firing wall from both the conventional low- NO_x boiler design and the DMB design, respectively. Both firing systems utilize exactly the

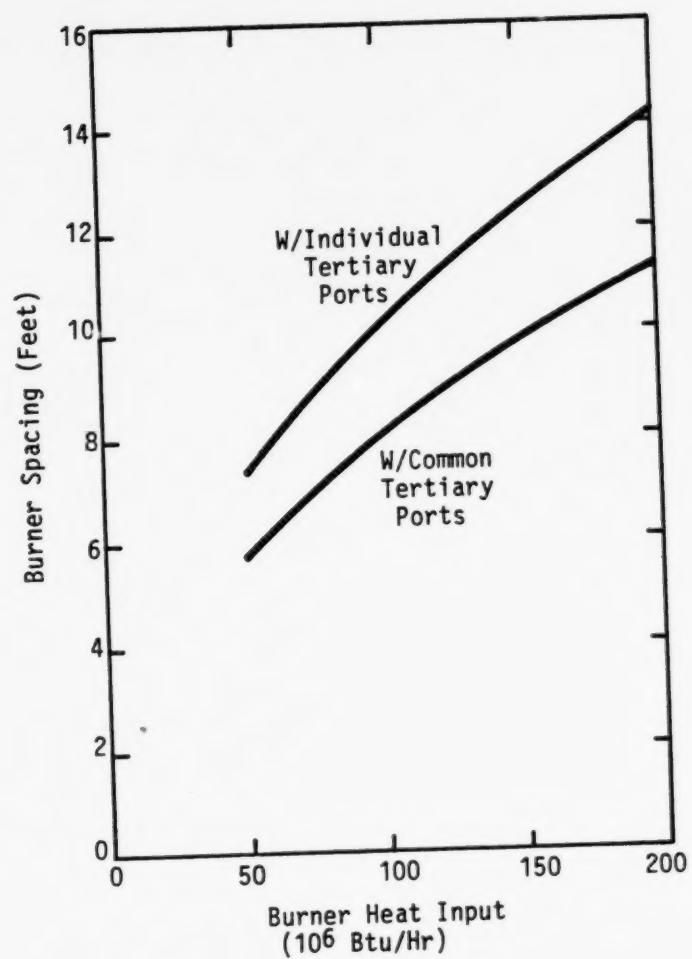


Figure 3-7. DMB boiler horizontal burner-to-burner spacing.

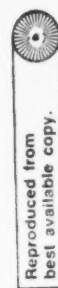


Figure 3-9. DMB firing wall.

same furnace size in all dimensions. This is accomplished, while still meeting the DMB design criteria by reducing the number of burners on each wall and by sharing tertiary air ports horizontally between burners. The cost impact of the change in firing wall design is discussed in Subsection 3.1.6.

Firing wall panel construction would not change from the conventional panels. Both panels would be of membrane wall construction utilizing 2-1/2 in. O.D. tubes spaced on 3 in. centerlines with a small bar welded between them to form a flat wall section. This typical design provides a continuous wall surface of high strength and gas tight construction. The panels are fabricated to dimensional limits of approximately 10 ft. x 50 ft. and are welded together at the construction site to form the furnace enclosure.

There are no changes to any of the conventional fabrication, shipping, or erection procedures as a result of the DMB application. However, there is a slight decrease in the erection effort required for the DMB application as each firing wall has only eight panels as opposed to ten on the conventional design. This will impact the field erection costs by reducing the number of crane "lifts" to complete the furnace wall and also by reducing the number of longitudinal welds that are made to connect the panels.

Figures 3-10 and 3-11 shows the secondary air duct and windbox arrangement for the conventional and DMB boiler designs, respectively. Note, for the DMB application, the additional air flow control dampers (one at each end of every compartment) and measuring air foils that provide control of the air flow through the tertiary air ports. Each horizontal windbox compartment must be further divided into two "sub-compartments" by the vertical partition plate that divides the windbox into two smaller windboxes, one for the burner air flow and the second for the tertiary port air flow. These design changes will be discussed in more detail in the following section.

It is important to determine the firing wall arrangement early in the new boiler conceptual design process as the balance of the windbox

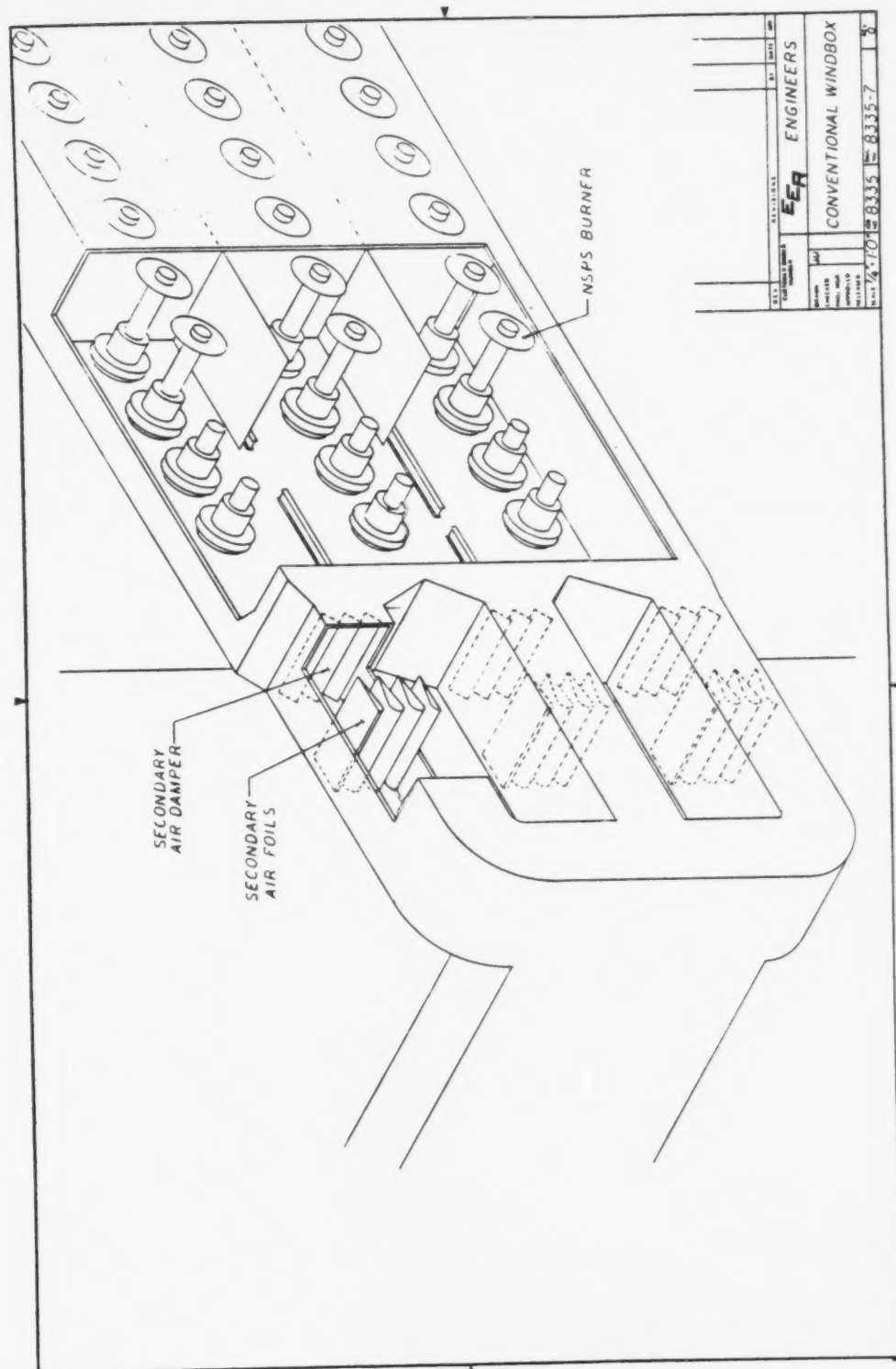


Figure 3-10. Conventional NSPS duct/windbox arrangement.

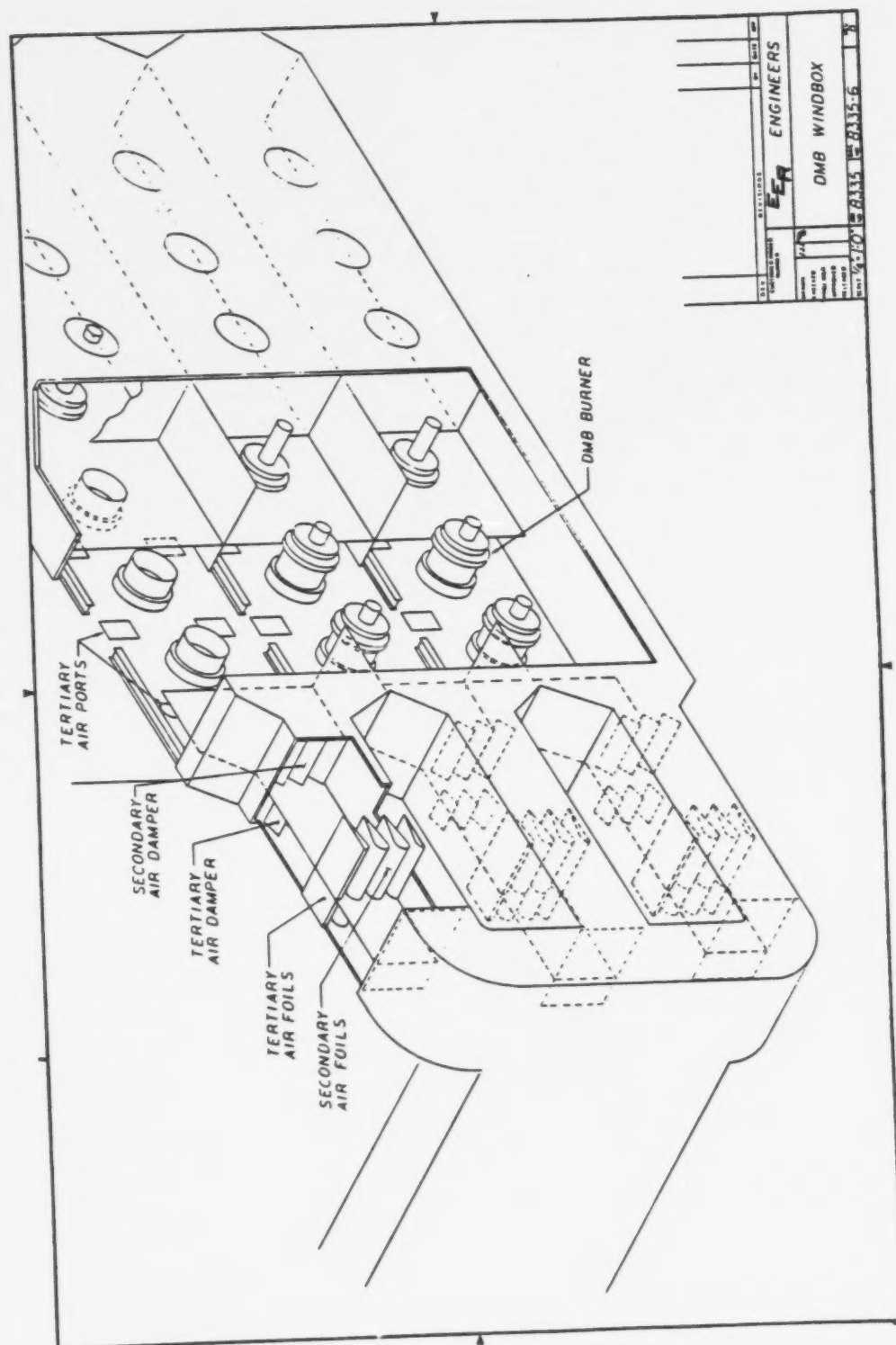


Figure 3-11. DMB duct/windbox arrangement.

arrangement, including the location of structural members in the windbox, is highly dependent on the burner throat and tertiary air port locations.

It does not appear that the application of the DMB to new boilers will impact the structural design to any significant extent. Although the windbox weight will increase somewhat due to the modifications necessary to measure and control both the burner and tertiary air flows, the weight of the burners will decrease. The results are an insignificant net weight change.

By utilizing a reduced number of burners and horizontally shared, rectangular port openings, the number of tubes in each firing wall requiring bending increases by only eight tubes. The conventional design requires 120 of the 291 wall tubes to be bent. The DMB design requires bending 128 tubes which will theoretically increase the loading on the remaining straight tubes by less than 5 percent. This modest increase will not require any structural modifications.

3.1.5 Operation and Control

The operation and control will differ from that of the conventional boiler only in that, above "control" load (65 percent), the total secondary air to the burners may be split between the burner flow and the tertiary air flow. Except for the added capability to measure and control that additional secondary combustion air stream, the boiler control system is unaffected by the DMB firing system arrangement. All turbine/generator, boiler, firing system, and flame safety systems are identical to those on a conventional boiler equipped with a typical NSPS firing system.

The DMB control philosophy is that, below control load, NO_x emissions are at acceptable levels without utilizing the staged combustion capability of the DMB design. Burner zone stoichiometries remain above 100 percent and the operating characteristics are much like those of a conventional NSPS burner. This approach will provide enhanced carbon burnout, flame stability, and burner turndown for better low load operation.

As boiler load increases above control load, the additional combustion air required will be admitted into the furnace through the tertiary air ports. At full load, enough air will be diverted through the ports to achieve the design burner zone stoichiometry of 70 percent resulting in minimum NO_x emissions. Figures 3-12 and 3-13 illustrate the air flow control function and burner zone stoichiometry relationship.

An alternate control approach could be used to reduce NO_x emissions further at low load. The burner zone stoichiometry could be maintained at the design point as load is reduced by reducing the secondary and tertiary air flows in parallel. This approach could be used down to the limit of burner turndown. Then one or more pulverizers could be removed from service for operation at lower load.

The measurement and control of the tertiary air port flow is a most important factor in the performance of the DMB firing system. The DMB-fired boiler designed for economic analysis utilizes a separate windbox sub-compartment for separating the burner and tertiary air flows. The air flow measurement and control can then be accomplished at only two points - each end of the compartment. This method is much more cost effective than an arrangement such as that utilized at the WIPCO demonstration where ports were controlled individually. With the windbox compartments arranged such that each compartment supplies only those ports associated with one pulverizer burner group, the group burner zone stoichiometry can be accurately controlled. On large boilers fired with a number of pulverizers, it is desirable to provide some form of tertiary port flow control in order to minimize the flow when pulverizers and burners are not being used. This assures low load boiler operation at acceptable excess air levels. In addition, as the DMB is operated at lower loads, the tertiary port flow can be held at the minimum flow required for cooling (approximately 10 percent design flow). This results in the DMBs operating at higher low load windbox-to-furnace air pressure differentials which results in better efficiency through reduced carbon loss and minimum excess air.

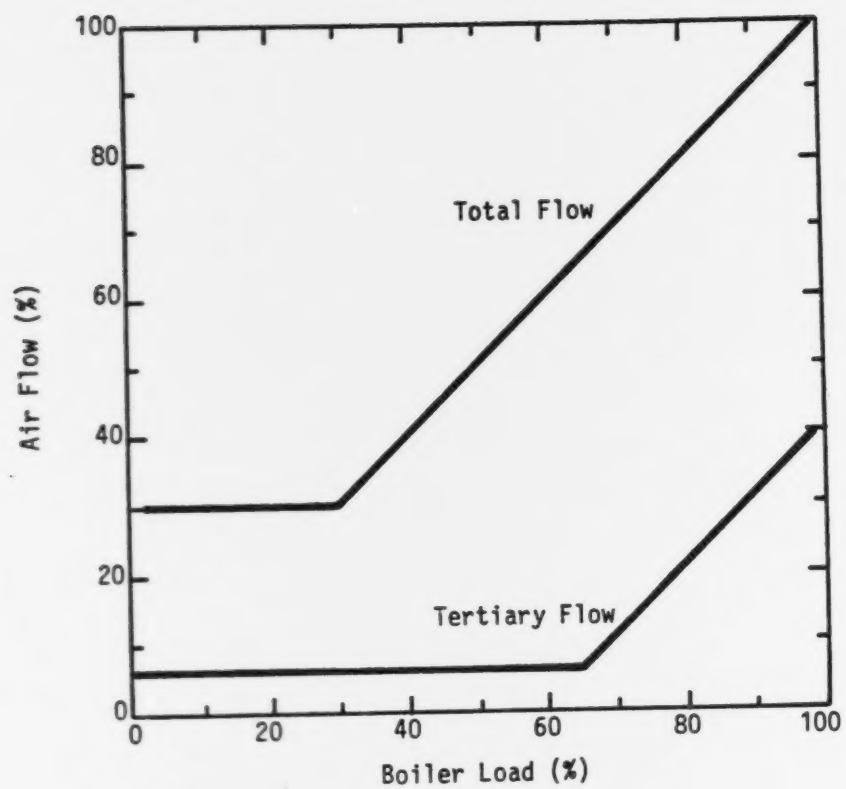


Figure 3-12. DMB boiler air flow.

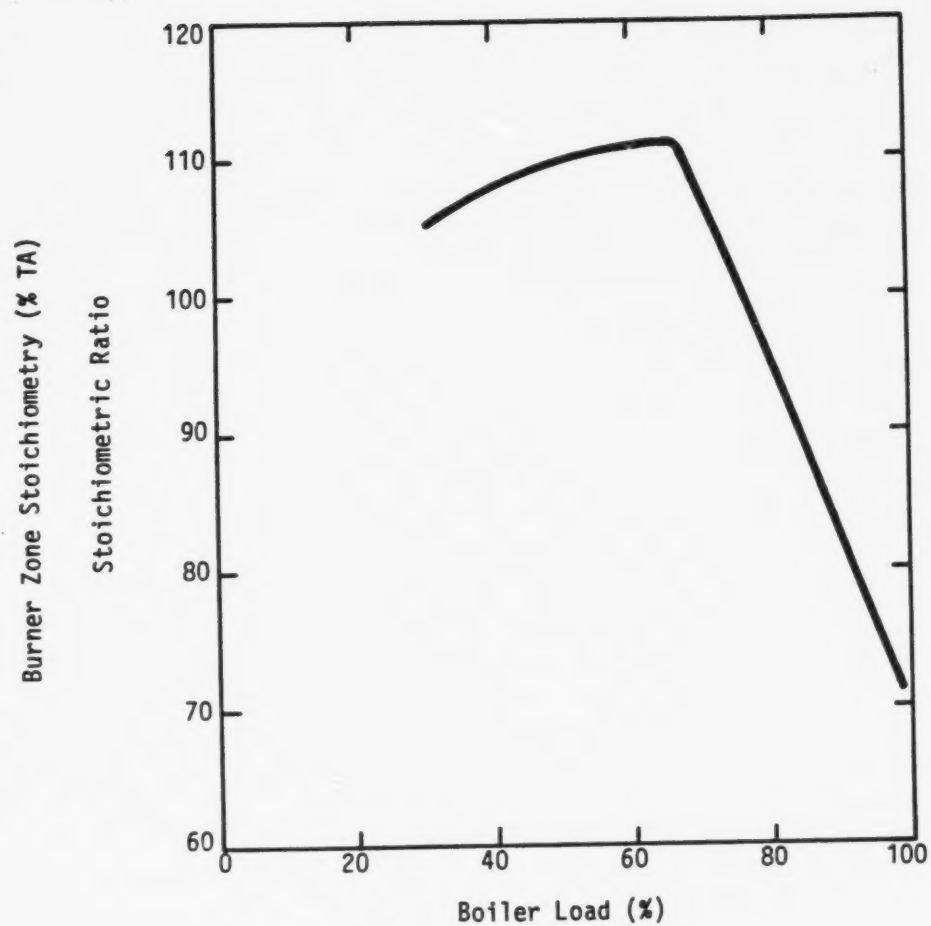


Figure 3-13. DMB boiler burner stoichiometry.

Historically, accurate measurements of air flow in large boiler ducts has been an area of concern for boiler designers and operators. There are occasional lengths of ductwork where the application of a venturi-type flow meter can be applied for measuring combustion air flows. Insufficient lengths of straight duct, varying air temperatures (up to 700°F) and pressure, and entrained fly ash particulates present a harsh environment for flow measurement instrumentation. Two alternatives available for flows in large ducts with straight runs too short for the application of a venturi metering section are air foils and honeycomb flow straightening sections followed closely by pitot static probe grids. The air foil flow meter is the most widely used flow metering technique in the utility industry. Figure 3-10 showed the application of air foils in the secondary air feeder ducts to each of the windbox compartments. Figure 3-11 illustrated the DMB modification required to add a second pair of air foils and dampers to measure and control the tertiary port flow.

Upon initial start-up, flow could be balanced to each port in the compartment using cold air. Once balanced, there would be no further monitoring of flow on an individual port basis. An alternative would be to add a control device at each port, adjustable during boiler operation, to obtain equal pressure drop, and therefore equal flow, across all ports. This was not included in the economic evaluation of the DMB application. Because the tertiary port flow is measured on an individual pulverizer basis, the desired stoichiometry will be maintained for each burner group even though there will be minor variations in individual burner stoichiometries due to occasional maldistributions of coal and air flows to individual burners within the group.

Figure 3-14 illustrates the only portion of the boiler controls affected by the DMB operating requirements, the fuel and air flow control subsystem. The schematic illustrates the data inputs to the system (circles) and the control signal outputs (hexagons). The addition of the DMB tertiary port air flow requires one additional control input, tertiary port flow, which is provided by the ΔP transmitter attached to each air foil flow meter. The system provides one additional output signal which operates the tertiary port

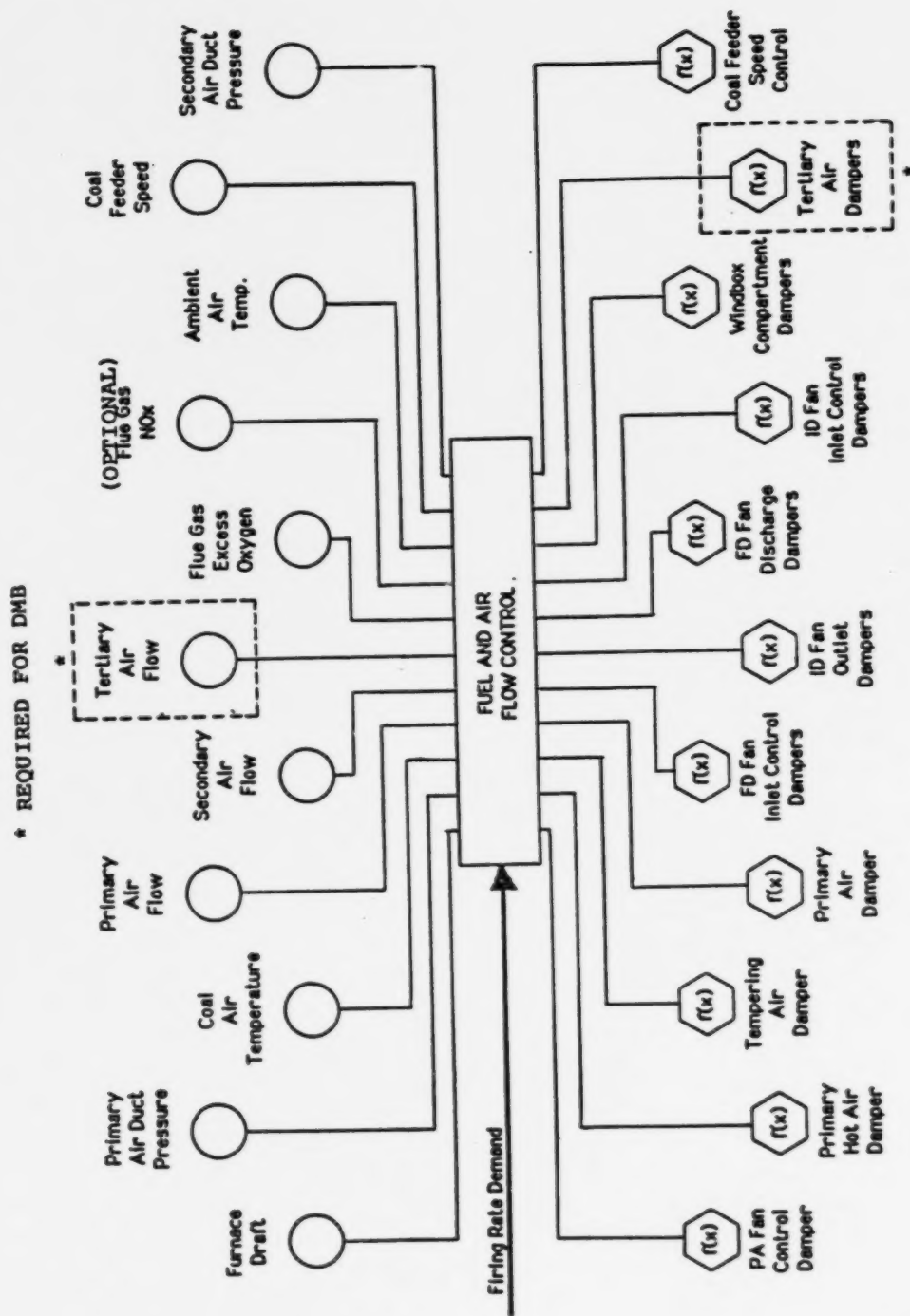


Figure 3-14. Control subsystem schematic.

damper drives as a function of load. An additional level of control could be incorporated by adding a flue gas NO_x concentration input signal. That signal could be used to further adjust the tertiary port flow and therefore provide a control loop that would continually adjust burner zone stoichiometry to achieve a desired NO_x emission level.

Figure 3-15 illustrates the air flow streams on the DMB boiler design and the important control points throughout the system.

3.1.6 Estimated Cost Impacts

The cost impacts estimated in this section are intended as a general indication of the changes that must be considered when applying a DMB firing system to new boiler designs; the costs shown are only approximate. Actual costs will be dependent on the burner design approach utilized by each manufacturer and on numerous factors which are influenced by individual boiler designs.

In order to fairly evaluate the relative cost of DMB applications, two "base" NSPS boiler designs must be considered which encompass almost all wall-fired domestic utility boilers presently offered. Case A is typical of an NSPS design that utilizes a relatively large number of burners (48 @ 112×10^6 Btu/hr) situated in a horizontally compartmented windbox (similar to the design shown in Figure 3-10). Case B is typical of an NSPS design that utilizes a smaller number of higher capacity burners (30 @ 180×10^6 Btu/hr) situated in a non-compartmented windbox. For the purpose of this study, it is assumed that the furnace dimensions are approximately the same for both designs assuming identical steam generation capacities. The Case A cost analysis is based on the assumption that the number of burners will be reduced to 36 while Case B requires no change in the burner quantity.

Each cost itemized is expressed as a differential cost that is based on comparing the equivalent engineering, fabrication, and material scope of a conventional NSPS boiler design with the DMB-fired boiler design. Each is

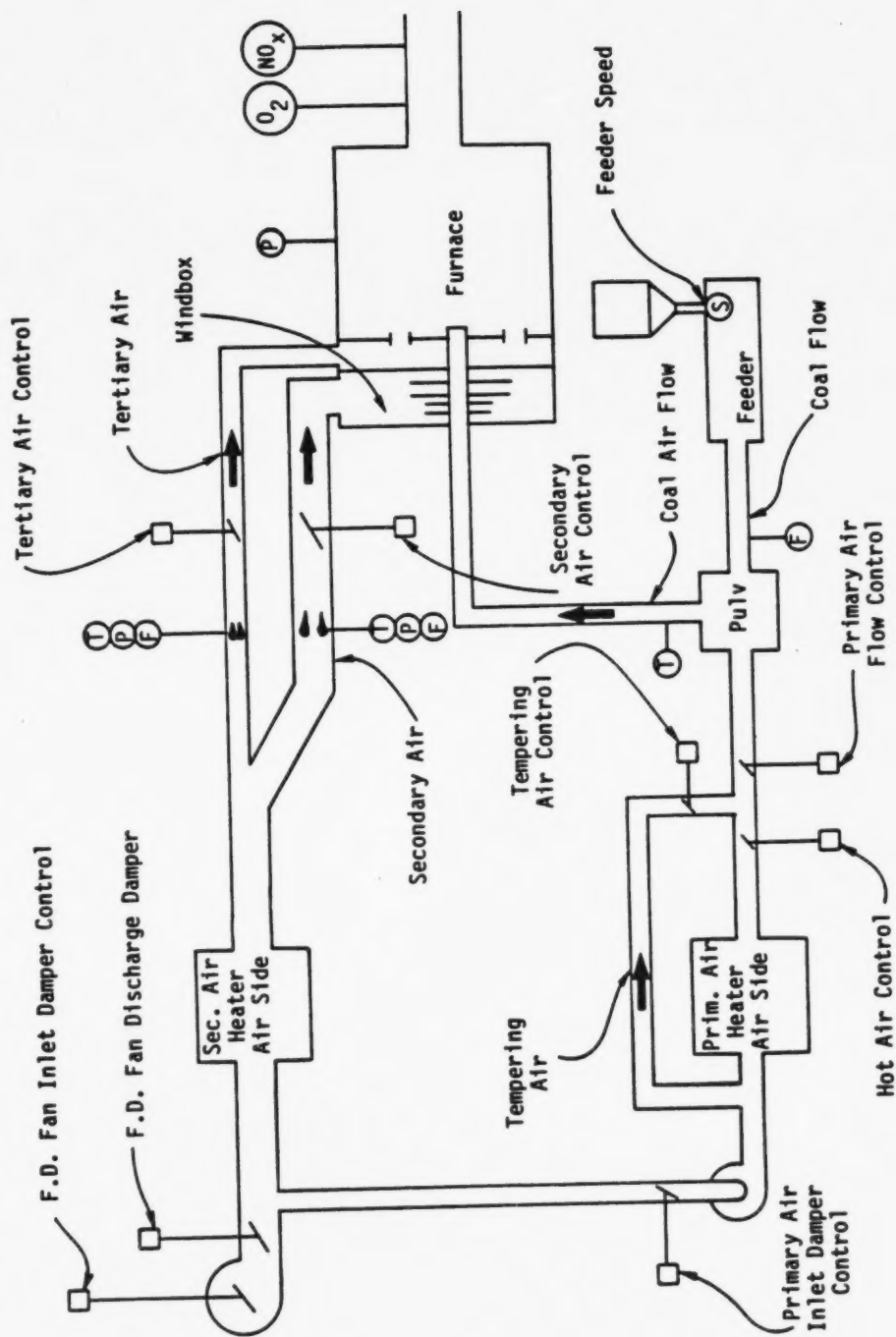


Figure 3-15. Air flow - DMB unit.

discussed below followed by a brief discussion of the impact of the changes on the erection of the DMB boiler design.

To provide a point of reference for these costs, the conventional NSPS boiler design (625 MW_e) studied would cost approximately \$55,000,000 (1986 dollars). Erection would be an additional \$29,250,000. The material scope of supply would include the following:

Summary of Major Equipment

Furnace (Primary and Secondary)
Superheater and Attemperator
Reheater and Attemperator Internals
Economizer
Tubular Air Heater (Primary)
Regenerative Air Heater
Steam Coal Air Heater
Pulverizers and Drives
Coal Feeders and Drives
Raw Coal Piping
Burners
Burner Piping
Lighters
Brickwork
Refractories
Insulation
Lagging
Thermocouples and Thermoprobes
FD-ID Fans and Drives
Recirculated Gas Fans and Drives
Primary Air Fans and Drives
Television
Steam Temperature Control
Integrated Boiler - Turbine Generator Control
Burner Control

Flame Monitoring Equipment
Structural Steel, including Platform Support
Top Support Steel (Grid), including Platform Support
Support Rods and Hangers
Platforms, Grating and Stair Treads
Soot Blowers and Drives
Recirculated Gas Dust Collector

Table 3-1, Terminal Points, further defines the scope of equipment included in the study.

The cost impacts of the DMB application to the Case A new boiler design is summarized in Table 3-2 and the cost impacts of the DMB application to the Case B new boiler design is summarized in Table 3-3.

Burners

The cost of the DMB itself can be assumed to be the same as an NSPS burner requiring a similar throat size provided by the same manufacturer. For the purpose of this study, the conventional NSPS burner with a 44" throat was assumed to cost \$18,600 and the 40" DMB \$18,000. As is always the case with new product applications, some additional engineering will be required on the first boiler application. However, it is not anticipated to be a significant increase as each manufacturer is expected to utilize his standard burner components for the DMB design.

A net savings is realized by the DMB approach due to the slightly lower burner cost (slightly smaller burner size). In the Case A boiler design, a significant savings is realized by utilizing a smaller number of higher capacity burners. A reduction in the number of burners is required to satisfy the DMB design criteria without changing the furnace width as discussed earlier in this section. In the Case B design, no savings can be assumed for a reduction in burner quantity.

TABLE 3-1. TERMINAL POINTS

Support Steel for Following Equipment

NOTE: Foundations, column base plates and anchor bolts are furnished by PURCHASER

Hangers and rods, nuts, and washers and bearing plates for support of drums, headers and tubes at top of unit

Horizontal support steel for support of drums, headers, and tubes at top unit, not including top framing of boiler columns

Miscellaneous Terminal Points

Blank connections at wall boxes for future soot blowers
Thermometer well connections as required
Draft connections as required
Air measurement connections as required
Blanked test connections for air and gas traverses

Piping

The PURCHASER furnishes all piping external to the boiler.

Safety valve relief piping to 8 ft. above top steel
Power control valve piping to 8 ft. above top steel
Water gauge and/or column drain piping terminating at a valve located at operating floor level
Drum pressure gauge to operating floor level
Piping for air motor drives for soot blowers from manifold at side of boiler
Air seal and aspirating air piping

The following Equipment is Furnished by the Purchaser within Terminal Points Listed:

Flue from economizer to primary and secondary air heaters
Air duct from primary and secondary air heaters to rear boiler columns
Steam coil air heaters

The Following Equipment is Furnished. To Be Installed By The Purchaser Within His Work:

Soot blower control panel for mounting on PURCHASER's control panel
Reheat attemperator sleeve and spray nozzle to be installed in PURCHASER's piping
Non-return valve
Power control valve
Superheater safety valves
Reheater safety valves

TABLE 3-2. CASE A DMB COST IMPACTS

Burners	\$<244,800.00>
Furnace Wall Panels	\$ 120,000.00
Windbox Division Plate	\$ 33,150.00
Controls:	
Air Foil Flow Meters	\$ 6,500.00
Dampers	\$ 32,060.00
Damper Drives	\$ 42,625.00
ΔP Transmitters	\$ 11,700.00
System Modifications	\$ 1,600.00
Miscellaneous	\$ 1,725.00
TOTAL COST DIFFERENTIAL	\$ 4,560.00

NOTE: Costs are intended to show trends and "order-of-magnitude" only. Individual applications will have to be priced in detail to determine the economic impact of DMB application.

TABLE 3-3. CASE B DMB COST IMPACTS

Burners	\$ <18,000.00>
Furnace Wall Panels	\$ 120,000.00
Compartmented Windbox	\$ 975,000.00
Controls:	
Air Foil Flow Meters	\$ 6,500.00
Dampers	\$ 32,060.00
Damper Drives	\$ 42,625.00
Δ P Transmitters	\$ 11,700.00
System Modifications	\$ 1,600.00
Miscellaneous	\$ 1,725.00
TOTAL COST DIFFERENTIAL	\$1,173,210.00

NOTE: Costs are intended to show trends and "order-of-magnitude" only. Individual applications will have to be priced in detail to determine the economic impact of DMB application.

Furnace Wall Panels

The cost of the furnace wall panels required for a DMB firing system will increase due to additional engineering and fabrication costs associated with the addition of tertiary air ports. The change in material cost is negligible. The difference in cost for producing the DMB panels compared to the NSPS base case panels is approximately \$60,000/wall or \$120,000 for both opposed-fired (front and rear furnace walls) boiler designs. This cost consists of approximately 85 percent additional material and fabrication cost and 15 percent additional engineering cost.

Windbox

The windbox modification described earlier is a fundamental part of the DMB firing system design. In review, the modification required to direct air flow independently to the burner throats and tertiary air ports includes dividing the windbox vertically in addition to the conventional horizontal divisions (available only in the Case A design). Carbon steel plates will be utilized for the vertical windbox partitions. The cost differential for the windbox modifications required for the DMB application on the base Case A boiler design is approximately \$33,150. Approximately 2/3s of that amount is material cost and 1/3 engineering cost. The two different windbox designs are indicative of the design approaches taken by two different manufacturers. Each has its own particular advantages and disadvantages. There are no other equipment or O&M costs that are impacted by the differences in windbox design.

The modifications required for the Case B design are considerably more extensive. In addition to the modifications required for the Case A design, additional ductwork, horizontal division plates, dampers, and air flow measurement modifications must be provided. The additional cost for these modifications, including engineering, erection, and materials, is on the order of \$975,000. While it was clear with the Case A boiler design that the windbox partitioning was the most cost-effective method of controlling burner

and tertiary air port air flows, other alternatives (individual tertiary port dampers or supply ducts, etc.) should be evaluated for the Case B design.

Controls

The measurement and control of the burner and tertiary air port air flows requires the addition of two metering devices (in this case air foils) and two control dampers for each burner elevation. The additional control elements required include a pressure differential transmitter for each air foil metering device added (in this case 12) and a damper drive for each tertiary port control damper (also 12). It may be possible to eliminate the extra control damper drives by linking the tertiary port dampers with the burner damper drives. However, at least for the first few boilers designed with the DMB system, the additional operating flexibility provided by the separate damper drives should be incorporated.

With respect to the control system itself, the cost impact of the addition of the tertiary port control damper logic to the balance of the firing controls would be minimal (\$1,600). With most modern digital control systems, the modification could simply be added to the system control program without any hardware changes.

The cost impact of the control system modifications required (including the additional drives) is approximately \$94,485.

These costs are assumed to be the same for both Case A and B boiler designs. The difference in windbox modification cost described earlier provides an equivalent arrangement from which to base the control modifications required.

Erection

The addition of a DMB firing system as part of a new utility boiler design would not significantly impact the erection cost of that boiler based on the information generated in this economic review. The decreased number

of burners would actually reduce erection labor required for burner installation (Case A only). The same is true, to a lesser extent, for the labor required to hang the furnace wall panels. Those reductions, however, will be more than offset by the increased labor required to install the DMB windbox (particularly for the Case B design). The additional measurement and control elements, but primarily the vertical partition plates, will increase erection labor requirements.

The combination of the various labor impacts will probably result in a slight increase in the total labor required for the boiler erection but it will only be a minor amount in the Case A design arrangement. The labor required to erect the windbox for the Case B design will increase significantly but the economic impact was included in the cost figure shown in Table 3-3.

Operating and Maintenance Impacts

While there will be slight increases to maintenance costs projected for DMB-fired boilers (additional dampers, drives, etc.) the cost impact will be minimal.

However, based on carbon losses observed during laboratory and field testing of the DMB to date, a significant operating cost impact could be projected. Using the 625 MW_e boiler example:

Coal Flow $\approx$ 500,000 lb/hr
Coal Heating Value $\approx$ 12,000 Btu/lb
Coal Ash $\approx$ 10 percent
Boiler Capacity Factor $\approx$ 65 percent
Coal Cost $\approx$ \$1.50/10⁶ Btu

Figure 3-16 illustrates the operating cost (fuel value only) incurred due to carbon losses in the boiler flyash and bottom ash. Additional costs must be considered due to the extra fuel and ash handled as the carbon loss

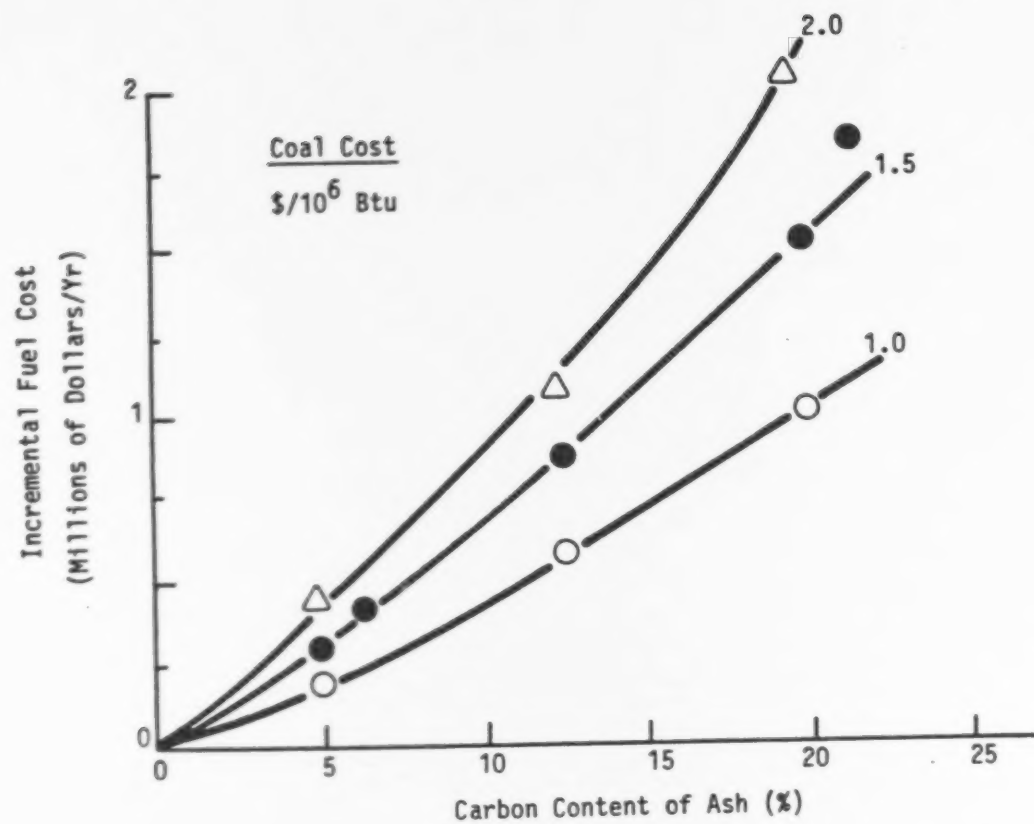


Figure 3-16. Operating cost impact due to carbon loss.

levels increase. Using conventional NSPS burners, the carbon content of the ash should be below 10 percent content.

There is not enough large-scale DMB operating data available to predict the increases in carbon losses, if any, that may result from the DMB application.

3.2 Applicability of DMB Retrofits to Existing Utility Boilers

The design, installation, and operation of the DMB firing system at WIPCO's Pearl Power Station was a valuable demonstration of its applicability to industrial and small utility pulverized coal-fired boilers. It also provided insight for applying the technology to larger utility boilers. As the boiler size increases and the steam cycle demands higher temperature and pressure boiler operation, the design complexity increases. This same complexity increases the amount of study required to fully evaluate the retrofit of the DMB system to larger boilers. Certainly for every retrofit application, a detailed engineering study will be required. This report can only identify those areas of concern that should be studied and convey any information derived from the program that may make those studies more meaningful.

Boiler design depends on size, manufacturer, outlet steam conditions required, age, structural configuration, and many other factors. Each boiler will present a unique set of challenges to retrofit the DMB firing system. However, in virtually all retrofit situations, space limitations and physical interference with existing equipment will be the primary impediment to the DMB retrofit. The simple burner/windbox designs, incorporated in pre-NSPS boiler designs, are difficult to adapt economically to the DMB system. The approach taken at Pearl Station, replacement of the firing wall and windbox, appears to be the cost effective one in most cases. It may be assumed that most smaller (<100 MW_e), single wall fired boiler retrofits will generally parallel the Pearl Station modifications quite closely.

The following are areas of concern that any potential retrofit candidate will face:

- Insufficient space between burners for tertiary air ports (inadequate furnace width)
- Inadequate furnace depth if increased flame length results
- Interference with windbox platforms and support steel
- Insufficient windbox depth for good air flow distribution to the burners and tertiary air ports
- Interference with coal piping
- Interference with downcomer piping
- Inadequate water circulation in the firing walls
- Insufficient firing wall structural length after DMB retrofit.

3.2.1 Furnace Size

In nearly all retrofit situations, the candidate boiler furnace width will not be adequate for retrofitting the same number of DMBs as original burners while maintaining the proper relationship of the tertiary air ports to each burner. Modification of the existing furnace size will, in most cases, be completely out of the question. Instead, a DMB retrofit will require some compromise of the design parameters usually coupled with a reduction in the number of burners. This should not present any significant difficulty on larger boilers with burner elevations consisting of five or more burners, providing that the flames from the larger burners can be accommodated in the furnace.

Retrofit candidates that utilize firing elevations with less than five burners may require more severe compromises of the DMB design parameters. Various aspects of the tertiary air port shape and location should be considered to minimize burner spacing and therefore furnace width requirements. The approach to making design parameter compromises is addressed in Subsection 3.2.5.

The furnace depth becomes a concern, particularly on smaller, single-wall fired boiler designs, because of the increased flame length that may result as a consequence of the DMB application. The flame length of the DMB can be adjusted to match that of the pre-NSPS burner design it replaces. However, by reducing the number of burners to enable the existing burner width to be utilized as discussed above, the heat input/burner will be increased. Flame length is a function of heat input and can usually be expected to increase as the heat input/burner increases. This effect may be offset by additional DMB adjustments to reduce flame length.

3.2.2 Physical Interferences

Many of the interference problems faced in any retrofit situation may be alleviated without a great deal of effort. Interferences such as cable trays, platform and stairway steel, plant utility air and water piping, etc. are examples. However, structural steel members can seldom be relocated without a great deal of expense.

In general, the DMB tertiary air port and boiler structural steel locations will determine the location of the balance of the windbox components. Most retrofits will be most economically completed by the redesign and replacement of the windbox entirely. Structural steel may also limit the maximum depth of the retrofit windbox. The increased number of burner registers and tertiary port air flow requirements may overcrowd the windbox causing flow distribution problems. This situation could contribute to higher unburned carbon losses.

Interferences with downcomer piping will occur only on higher pressure boilers without convective section boiler banks. The smaller, low pressure units will usually utilize downcomer piping in the rear of the boiler, away from the firing wall and retrofit area. In contrast, the majority of downcomer piping on larger boilers is located near the front wall, many times routed through the windbox itself. This piping generally has a minimum nominal diameter of 12 inches and very thick walls.

Even supercritical, "once through" designs, which do not utilize a steam drum with several large downcomers for liquid recirculation, have numerous, smaller downcomers to supply the various furnace circuits which must be considered. In addition, those designs often have large mixing headers located at various locations adjacent to the furnace which would be extremely expensive to relocate.

While rerouting downcomer piping is not impossible, it is a very costly modification.

3.2.3 Waterside Circulation

The possible impact on waterside circulation in the firing walls should be evaluated. Due to the increased number of tube bends required to locate the tertiary air ports in the firing walls of the candidate boiler, the resistance to flow of the steam/water mixture inside the bent tubes increases. If the flow resistance becomes high enough, the flow will drop below the minimum required to keep the tube from overheating, and consequently, failing. This concern becomes increasingly important as the design pressure of the boiler increases. In higher pressure designs, the difference in specific volume between saturated vapor and liquid is less, therefore the natural circulation head in the boiler tube circuits is lower. It is this circulation head pressure that causes waterside circulation to occur, unassisted, in all natural circulation boiler designs.

3.2.4 Structural Considerations

The DMB installation experience at the Pearl Station is exemplary of the structural considerations that must be addressed for any DMB retrofit. The primary impact of the DMB design on the structural system is related to the number of tubes bent in the firing walls for the tertiary air ports. The tubes which are bent to form openings in the furnace wall are no longer considered to have any significant load carrying capability. Therefore, if the number of straight tubes that remain to support the lower portion of the boiler wall and hopper slope is inadequate, other methods must be employed to support that weight. Subsection 3.2.5 addresses tertiary port design alternatives which can minimize the number of wall tubes requiring bending.

It is reasonable to expect that most industrial DMB retrofits would require very similar structural modifications to the Pearl unit. Relatively small furnaces with single wall firing should have enough strength in the sidewalls to carry the additional loads.

As boiler size increases, the loads encountered as a result of heavier wall tubes, additional burners and tertiary ports, and firing from two walls may not simply be transferred to the side walls. Another means of support such as spring hangers attached to the main structural members or lower furnace support from grade will have to be employed.

It may also be necessary to verify that the boiler support columns can handle the additional loads. Additional support steel may be necessary in some cases.

3.2.5 Retrofit Compromises

The initial approach to DMB application should be based on the design parameters listed in Section 2.0. In most retrofit situations it will be necessary to make some design decisions that will result in a retrofit DMB firing system that does not exactly conform to these parameters. This will possibly result in less than optimum NO_x emissions performance. However, the

decrease in emissions performance may be small enough to enable the retrofit boiler to achieve the desired emissions goal. This section will discuss some of the possible compromises and design alternatives available for applying the DMB to existing boilers.

Tertiary Port Design

The design of the tertiary ports significantly impacts the furnace width required for the DMB firing system. At the same time, the port shape determines the number of wall tubes that require bending and consequently, impacts retrofit costs, waterside circulation, and structural considerations as discussed above. The first compromise to the DMB design parameters considered should be the design of the tertiary ports due to the close burner to burner spacing in virtually all multiple burner applications, the design should assume that ports are shared between each two burners in the horizontal direction. This will reduce the furnace width required for DMB retrofit. The impact of port sharing is discussed further in Subsection 3.1.4.

Figures 3-17 through 3-20 illustrate a section of boiler furnace wall area that accommodates the DMB design approach. Each shows two burner throat openings in the wall and associated tertiary air port openings. A few of the tubes that form the wall are shown for illustrative purposes. The wall openings are formed by bending tubes out of the plan of the wall and to the sides. In each figure, the flow area of the tertiary port openings are equivalent to those shown in the other figures.

Figure 3-17 shows the circular tertiary port arrangement which was used during the development of the DMB and, subsequently, for the WIPCO retrofit. The round configuration represents the "worst" case from the number of tube bends required to achieve the desired flow area. The first compromise to consider for reducing the number of wall tubes bent is that of port shape. Figures 3-18 through 3-20 illustrate several alternative port arrangements that reduce the number of bent tubes required while maintaining the DMB port parameters for flow rate and velocity.

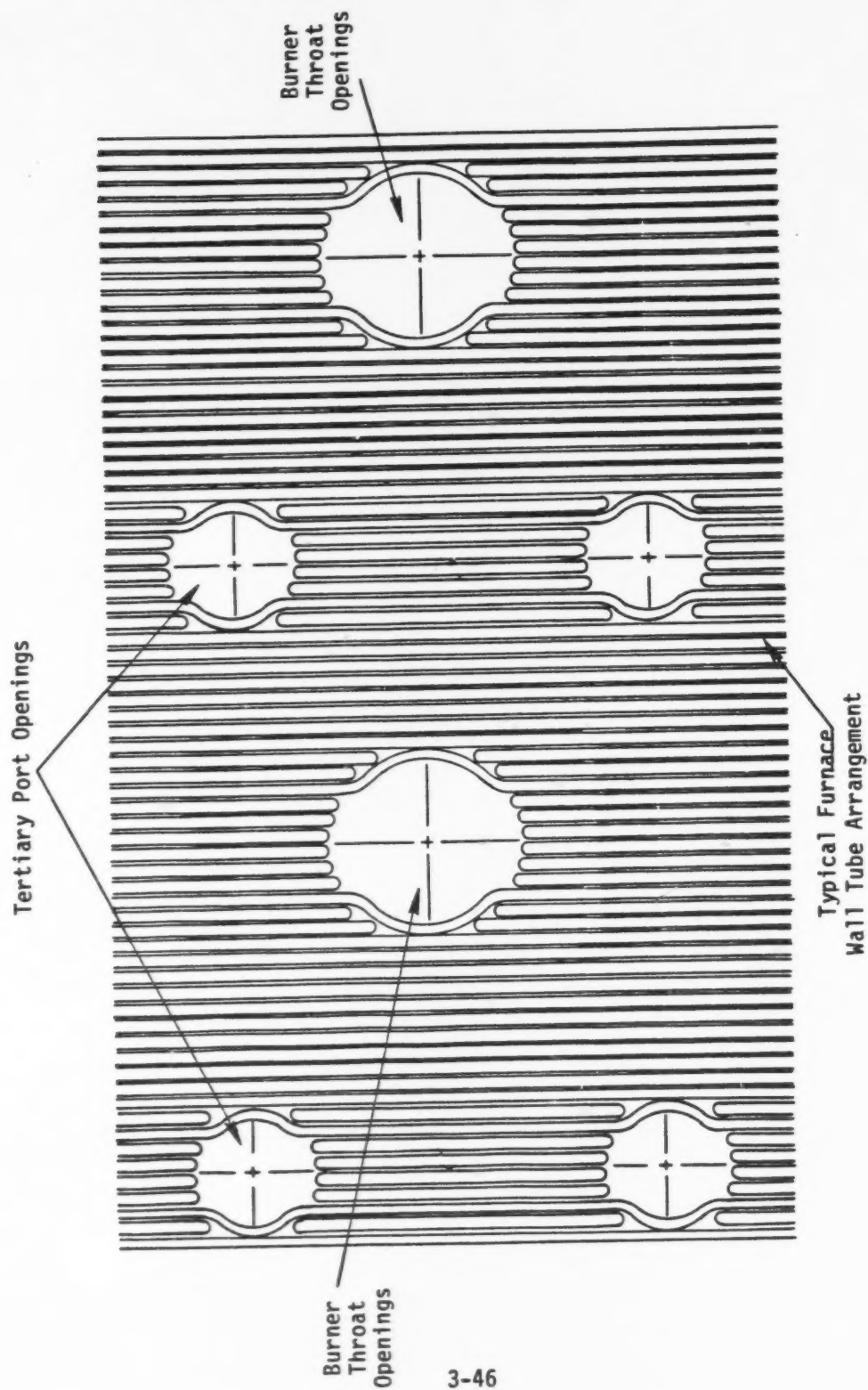


Figure 3-17. Circular tertiary port design.

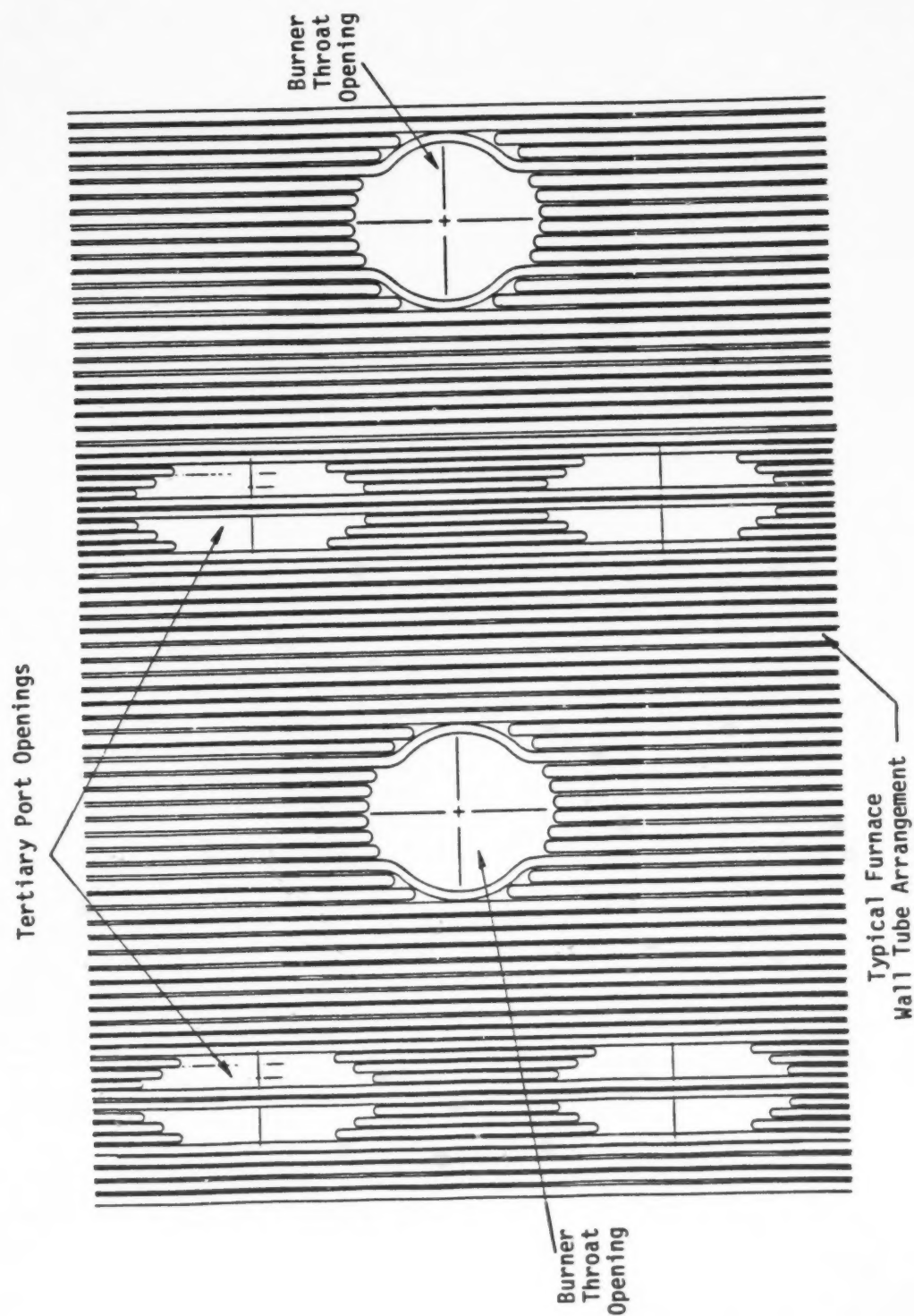


Figure 3-18. Slightly elongated tertiary air port with division.

Tertiary Port Openings

Burner
Throat
Opening

Burner
Throat
Opening

Typical Furnace
Wall Tube Arrangement

Figure 3-19. Elongated tertiary air port design with division.

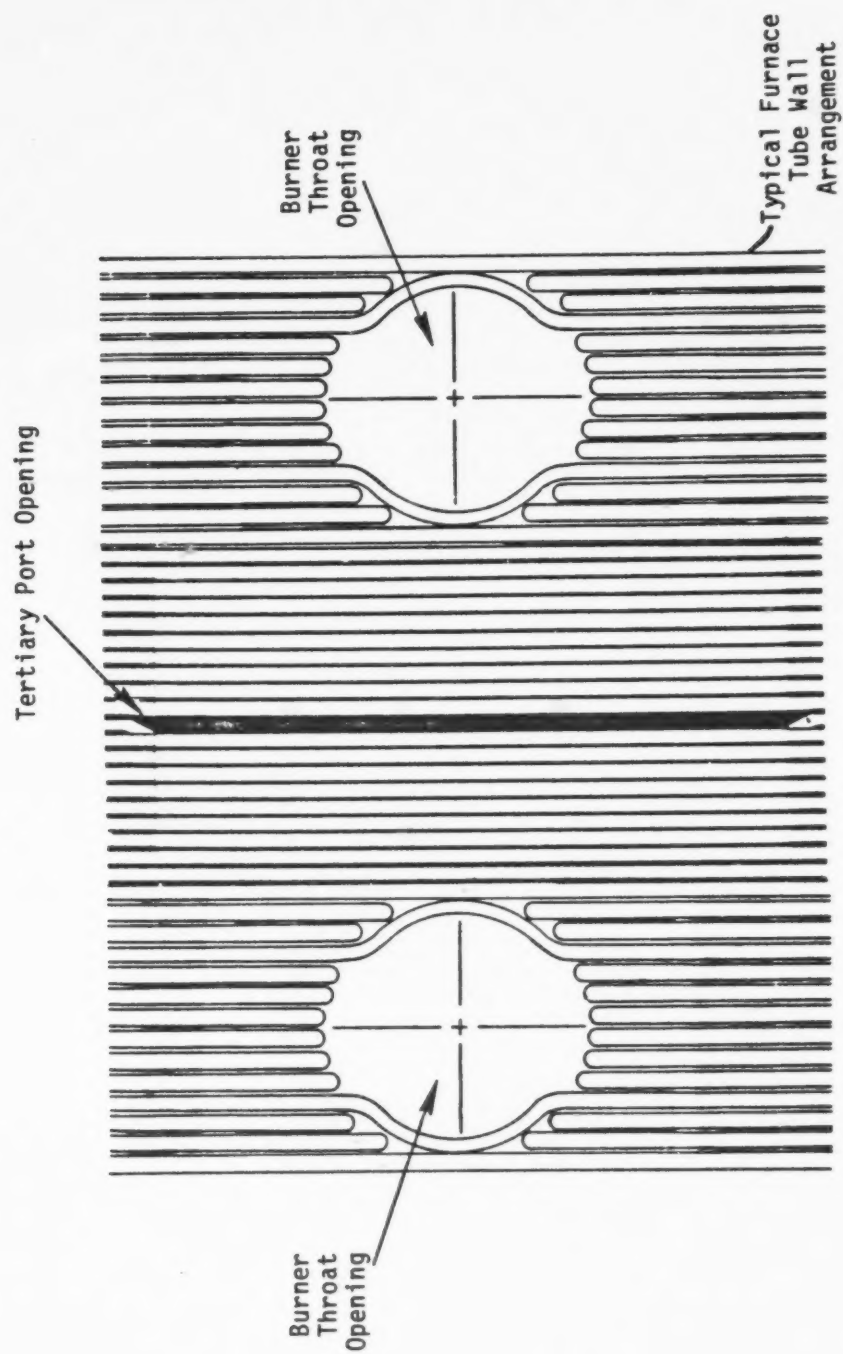


Figure 3-20. Elongated shared tertiary air port design.

A second compromise which should be considered is that of port location. The burner spacing and furnace width required are directly effected by the radial distance between the tertiary ports and the burner throats. Development testing of the DMB concept has shown that, as the distance increases, NO_x emissions decrease. Other factors such as burner carbon conversion efficiency, practical constraints on flame length, the probability of contact between furnace wall surfaces and reducing gases, have lead to the decision to limit the port radial distance to 2.2 throat diameters. In the typical retrofit case, with close burner spacing a compromise must be made to reduce the distance to the tertiary ports. Previous small-scale DMB testing indicates that the ports should not be located closer than 1.5 throat diameters from the burner centerline or NO_x emission reduction becomes ineffective.

Based on the results of the isothermal tertiary air port mixing study and the results of the full scale field evaluation at WIPCO, the burner to burner spacing and design of the tertiary air port array may have major impacts on the ability to balance the burners. Flow mixing tests should be incorporated into the design process to minimize any tendency for non-uniform tertiary air entrainment. The preferred approach is to avoid shared ports if possible. If shared ports are required, the tertiary velocity should be increased to reduce imbalance problems.

Burner Throat Design

The reduced secondary air flow rate and reduced secondary velocity of the DMB compared to conventional burners generally result in DMB throat diameters comparable to conventional pre-NSPS burners, this suggests a very low cost approach to DMB retrofit: no changes to the existing burner throat. Small deviations from the DMB design velocities would probably not be significant. However, the burner flame stability should be evaluated in a fired test. Throat sizes for DMBs are discussed in Subsection 3.1.4.

4.0 DMB PERFORMANCE

4.1 NO_x Emissions

The primary reason for selecting the DMB over less complex conventional burners is low NO_x emissions. The results of the DMB tests in research furnaces and the field evaluation have shown that NO_x emissions of less than 0.3 lb/10⁶ Btu could be obtained in all cases. However, it is well known that NO_x emissions are influenced by the furnace confinement and thermal environment as well as the specific burner designs.

As part of the DMB development program, DMBs with a range of firing rate capacities were designed according to the DMB design criteria and tested in a single furnace. Evaluation of these data provide an indication of the effects of burner scale. In other tests, specific burners were tested in two furnace enclosures. This provides an independent evaluation of furnace confinement variables.

The results are summarized in Table 4-1 as four comparisons. Comparison 1 involved several single secondary development DMBs tested in two research furnaces as individual burners and a 2 x 2 array. The data showed that increasing burner capacity and total heat liberation rate simultaneously in a fixed furnace enclosure increased NO_x emissions. NO_x emissions were approximately proportional to the furnace heat release for cooled surface area (Q/A). There was no measurable difference in NO_x emissions between the single 50 x 10⁶ Btu/hr burner and the 2 x 2 array of 12.5 x 10⁶ Btu/hr burners (same total heat release rate) under balanced burner conditions.

In Comparison 2, the initial prototype burner was tested in two furnaces with similar geometry but different thermal environment. The new LWS had refractory insulation while the old LWS had only water cooled surfaces. The increased Q/A of the new LWS did not increase NO_x emissions.

Comparison 3 involved firing the DMB design used for the field evaluation and two furnaces with similar thermal environment (Q/A) but

TABLE 4-1. EVALUATION OF DMB RESEARCH FURNACE DATA

Comparison Number	Burner	Capacity 10 ⁶ Btu/hr	¹ Furnace	Principal Variable	Effect on NO _x Emissions
1	Single Secondary Development DMBs	100	Old LWS	Burner Capacity	Increase with Furnace Q/A Flame Interactions Insignificant
		50			
		4 x 12.5			
			12.5	Old SWS	
2	Initial Prototype DMB	70	Old LWS	Furnace Insulation	No Effect of Q/A
			New LWS		
3	Final Prototype DMB	70	New LWS MT	Furnace Confinement	Increase in Smaller Furnace
4	Versatile Burner	10	New SWS	Furnace Insulation	No Effect at DMB Conditions, Increase at Unstaged Conditions

¹ EER Test Facilities:"Old LWS": 100 x 10⁶ Btu/hr capacity; built 1975 (no refractory lining on sidewalls)"New LWS": 100 x 10⁶ Btu/hr capacity; built 1981 (refractory on sidewalls)"MT": 50-70 x 10⁶ Btu/hr capacity"Old SWS": 12.5 x 10⁶ Btu/hr capacity"New SWS": 10 x 10⁶ Btu/hr capacity

different size. In particular, the MT furnace severely confined the flame. NO_x emissions were higher in the compact furnace probably because the furnace confinement altered the DMB fuel/air mixing patterns.

The final comparison involved tests of a small DMB under staged and unstaged operating conditions in a furnace with variable thermal insulation. Increasing the furnace insulation (Q/A) had no effect on NO_x emissions under DMB conditions but a significant increase resulted under unstaged conditions.

Based on all available research furnace data, it appears that furnace design and burner to burner interactions have little effect on NO_x emissions providing that the furnace confinement does not alter the DMB fuel/air mixing. However, this analysis was based on research furnace data only and the furnace thermal environments were "colder" than those of many larger commercial operating boilers.

The field evaluation at WIPCO provides data in a "hotter" thermal environment. Figure 4-1 is a plot of the research furnace data and the WIPCO data at full load with optimum burner settings as a function of the furnace thermal environment. Foster Wheeler's burner zone liberation rate (BZLR) was used as the thermal parameter. For comparison, Foster Wheeler's published correlations for the pre-NSPS intervane burner have been shown also.

The DMB NO_x emission data are in the range of 0.1 to 0.3 lb/10⁶ Btu. The WIPCO data are at the hottest thermal environment but are comparable to the highest NO_x emission data in the coldest research furnace, the old LWS. This confirms that the thermal environment has little effect on NO_x emissions, at least over the range of these data.

The DMB has not been tested in furnaces with thermal environments hotter than that of the WIPCO boiler. Therefore, NO_x emissions for DMBs apply to hotter thermal environments can only be estimated by projection. The dotted lines in Figure 4-1 show the range of DMBs NO_x emissions which can reasonably be expected from the DMB. These lines were drawn to include all DMB data with trends similar to the Foster Wheeler pre-NSPS burner correlations.

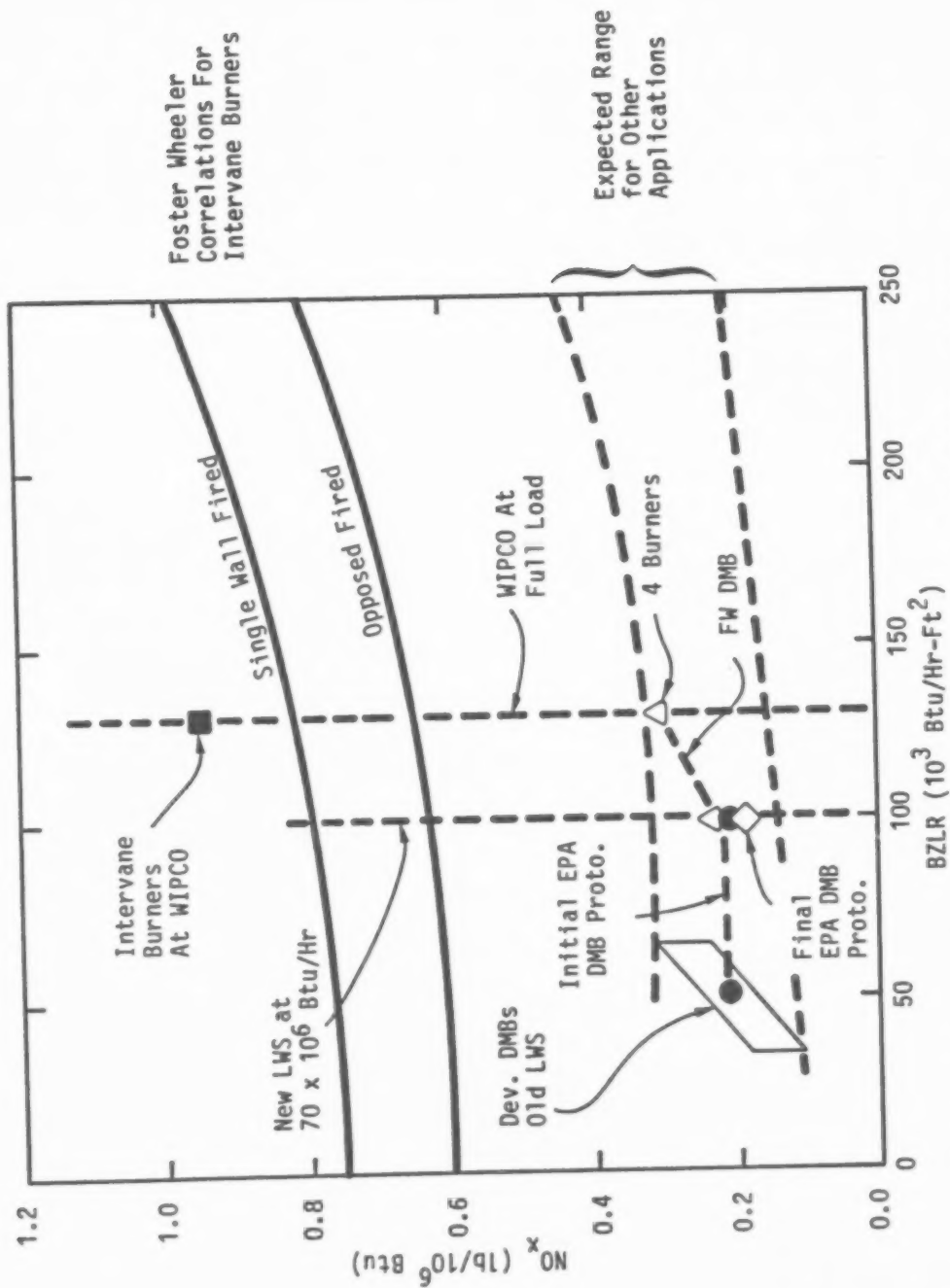


Figure 4-1. Projection of research furnace and field NO_x emission data.

This projection indicates that NO_x emissions from the DMB should be less than about $0.4 \text{ lb}/10^6 \text{ Btu}$ even for hot thermal environments. It should be recognized that these projections were based on the DMB performance in research furnaces and at WIPCO under optimum balance burner conditions. However, balanced conditions were difficult to achieve at WIPCO. Thus, the projections in Figure 4-1 assume that future DMBs can be designed to avoid these problems.

4.2 Combustion Efficiency and Burner Balancing

Under optimum operating conditions, DMBs can be adjusted to produce a carbon loss of less than 1.0 to 2.0 percent. However, the DMB is inherently sensitive to burner balancing and imbalance can increase carbon loss substantially.

Section 2 discussed the effects of burner zone stoichiometry on the performance of the DMB. Briefly, NO_x emissions are reduced by lowering the burner zone stoichiometry; however, CO emissions and carbon loss increased rapidly as burner zone stoichiometry is reduced beneath a threshold of about 50 to 70 percent theoretical air depending upon the burner design parameters. Since the primary reason for selecting the DMB is low NO_x emissions, the DMB should be operated at the lowest possible burner zone stoichiometry commensurate with adequate combustion efficiency. As a result, the DMB performance is very sensitive to burner balance.

Figure 4-2 illustrates the effect of burner balance on NO_x emissions and carbon loss for an array of two DMBs. Operation at high burner zone stoichiometry and DMB conditions are illustrated. The lines shown and the open symbols refer to the operation of the individual burners. The solid symbols refer to the average performance of both burners.

Since the trend of NO_x emissions versus burner zone stoichiometry is approximately linear, burner imbalance has no effect on NO_x emissions: the NO_x emissions for an unbalanced two burner array are the same as that

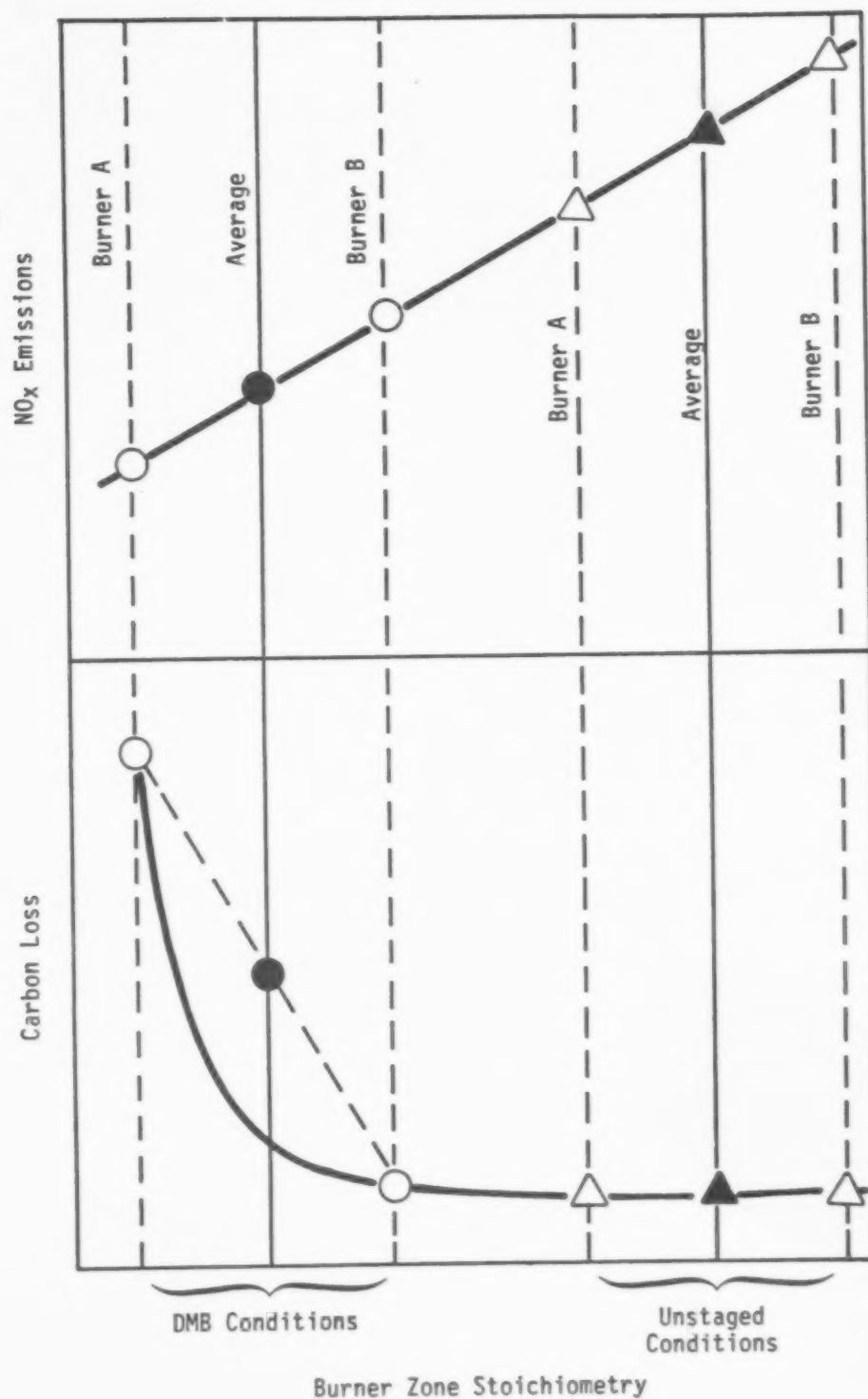


Figure 4-2. Effects of DMB imbalance.

produced by a single burner operating at the average burner zone stoichiometry. This is true for both DMB and unstaged operating conditions.

The trend of the carbon loss versus burner zone stoichiometry is a knee shaped curve. For high burner zone stoichiometry or unstaged conditions, burner zone stoichiometry has no effect on carbon loss and thus burner imbalance is unimportant. However, under DMB conditions, the carbon loss trend is non-linear. Burner imbalance greatly increases carbon loss because the burner(s) with the lower burner zone stoichiometry operate past the knee of the curve.

While Figure 4-2 applies directly to an array of two DMBs, similar effects can occur with larger arrays including the four burner array evaluated at WIPCO. The overall effect is that for high NO_x and high burner zone stoichiometry operating conditions, burner imbalance has little effect on NO_x or carbon loss. However, as burner zone stoichiometry is reduced and NO_x emissions decrease, burner balance becomes increasingly more important and becomes critical for operation under DMB conditions.

Due to the importance of burner balancing, future DMBs should be designed with extra attention to fuel and air flow distribution among the burners and tertiary air ports. Fuel distribution among pulverizers can be controlled easily via feeder speeds; however, it is difficult to balance the burners supplied from a single pulverizer. In most installation, it will be necessary to accept some imbalance in the fuel supplied to the burners and to control burner zone stoichiometry by means of balancing the air flow.

The DMBs installed at WIPCO had an air flow meter on each burner passage and tertiary air port. Nevertheless it was difficult to adjust the burners for balanced performance and to maintain balanced operation without continuous operator attention. These problems are discussed in detail in Volume 1 of this report. Based on all available information, it appears that the difficulties in balancing the burners at WIPCO are probably due to the close burner to burner spacing and the use of "shared" tertiary air ports between the burners. This is illustrated in Figure 4-3 for two DMBs with a

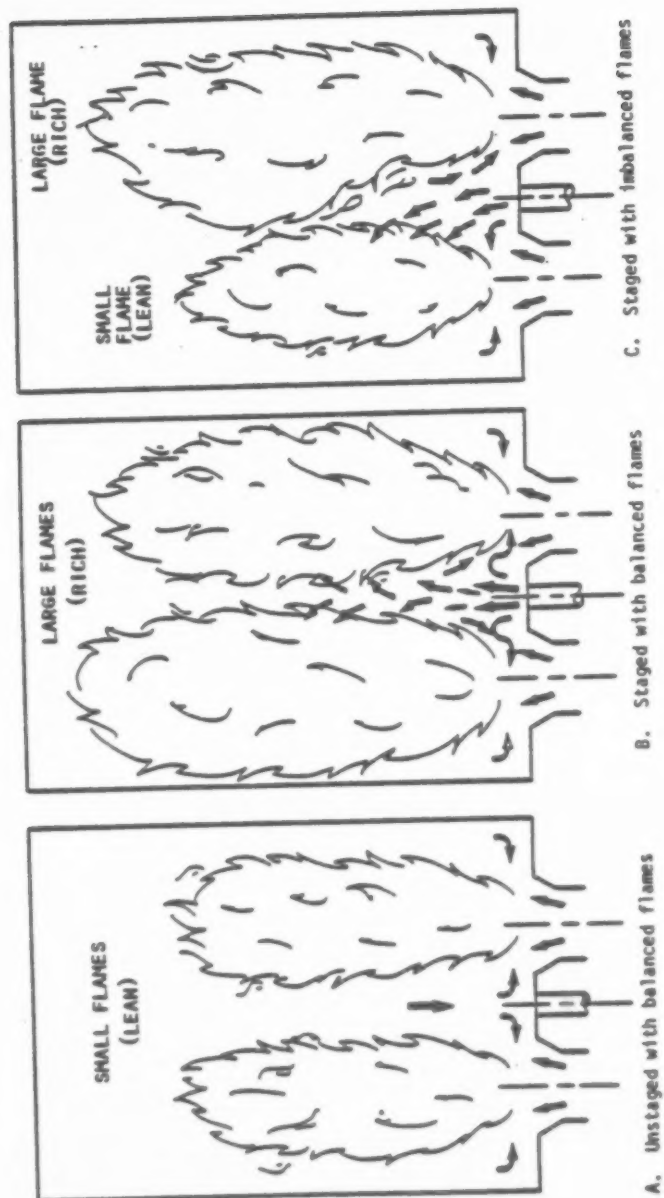


Figure 4-3. Tertiary air mixing patterns.

shared tertiary air port between them. The typical performance under unstaged conditions is illustrated in Figure 4-3a. The unstaged flames are relatively small and operate essentially independently. The recirculation within the flames entrains flow from along the firing face. This results in an inward flow direction between the burners.

Figure 4-3b illustrates operations under ideal staged (DMB) conditions. Since the flames are substoichiometric, they are larger than the unstaged flames. They may be wider at the base also due to high swirl. Ideally, the flow from the tertiary air port between the burners would mix uniformly with both flames following the DMB concept. However, the flow from the tertiary air port is in a direction opposite to the flow without the port. For some conditions, the imbalanced flow illustrated in Figure 4-3c could occur. Here the air flow from the port between the burners is preferentially drawn into one of the flames. This increases the available oxygen in that flame reducing its size. The other flame operates at reduced stoichiometry with lower entrainment power. Under some conditions this imbalanced flow pattern may be more stable than the balanced flow pattern and the flow from the tertiary air port may even switch between flames. This bistable flow could occur with the center port as shown or could occur with other ports or perhaps in combination with a "coanda" effect where the tertiary air flow becomes attached to a furnace wall. It is possible that switching between flow conditions could occur in response to changes in some input variables such as the pulverized coal flow rate, burner firing rates, excess O₂ etc.

To evaluate these effects, isothermal tests of a shared tertiary air port between four burners were conducted at small scale. These tests showed that slight imbalances between the flow rates in each burner caused the tertiary air to be entrained preferentially into the higher flow rate burner stream. In a fired system, this would have the effect of amplifying any burner to burner imbalance. For example, if four DMBs shared a central tertiary air port (as at WIPCO) and one burner had slightly greater entrainment power, the flow from the central port would be entrained preferentially into that flame tending to make the other flames operate more fuel rich with higher carbon loss.

To minimize carbon loss and burner balancing problems, future DMB arrays should be designed to minimize burner to burner interactions. This suggests designs with wide burner to burner spacing and avoidance of shared tertiary air ports. However, as discussed in Sections 3.1.5 and 3.2.4, some compromises will have to be made. To minimize boiler furnace size (and therefore cost), maximizing tertiary port sharing between burners is dictated. On the other hand, minimizing port sharing will minimize unburned carbon losses. It appears that sharing ports in only one direction, and between no more than two burners, will result in acceptable NO_x emission reduction and carbon loss performance. Economic evaluation of carbon loss (an operating cost) and boiler cost (a capital cost) will have to be performed for each individual boiler case.

4.3 Ignition and Flame Detection

The DMB is compatible with conventional coal burner ignition and flame detection equipment. No problems were identified in the field evaluation utilizing conventional burner components. The DMB installation at WIPCO included a spark ignited light fuel oil fired ignition system mounted on the burner centerline. Two infrared flame scanners were used: the one for the ignitor flame was mounted on the ignitor assembly near the burner centerline. The main flame scanner viewed the flame through the secondary air passage.

The ignition sequence was controlled by a new burner management system. The normal sequence involved lighting the ignitors with the tertiary air ports closed. The pulverizers were then brought on-line and then the ignitors were extinguished. The tertiary air ports were then opened and the burners were adjusted to DMB conditions.

4.4 Impacts on Boiler Performance

The only impact of the DMB on boiler performance identified during the field evaluation program was an increase in carbon loss under imbalanced burner operating conditions as discussed in Section 4.2. The DMBs could be operated with the normal excess air, 3.3 percent O₂, at the full boiler

capacity. Due to the design of the tertiary air port control system, the windbox to furnace pressure differential was reduced considerably providing an additional margin of fan capacity and decreasing auxiliary power consumption slightly. Steam temperatures with the original equipment burners and DMBs were similar.

During the test program there were several instances of lower furnace slagging. However, during the program, WIPCO purchased a wide range of coals of varying quality on the spot market. In addition, pulverized coal fineness was found to be poor at several times. Both poor coal quality and coal fineness are known to promote slagging. However, there is no way to determine if the DMB contributed directly to the occurrences of slagging during this program. Ash deposits were observed to build up on the firing face within the array of tertiary air ports. Occasionally, highbrows would buildup around one or more of the burners. Ash deposition on the hopper was also a problem in some instances and in one case an outage was required to remove the ash deposits.

Tube wastage rates were monitored throughout the program with both the original equipment burners and DMBs in service. In both cases, tube wastage rates were very small and there was no measurable increase during DMB operation.